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Spectral Studies of Asteroids 21 Lutetia and 4 Vesta as Objects of Space Missions

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Abstract—Asteroid 21 Lutetia is one of the objects of the *Rosetta* mission carried out by the European Space Agency (ESA). The *Rosetta* spacecraft launched in 2004 is to approach Lutetia in July 2010, and then it will be directed to the comet Churyumov–Gerasimenko. Asteroid 4 Vesta is planned to be investigated in 2011 from the *Dawn* spacecraft launched by the National Aeronautics and Space Administration (NASA) in 2007 (its second object is the largest asteroid, 1 Ceres). The observed characteristics of Lutetia and Vesta are different and even contradictory. In spite of the intense and versatile ground-based studies, the origin and evolution of these minor planets remain obscure or not completely clear. The types of Lutetia and Vesta (M and V, respectively) determined from their spectra correspond to the high-temperature mineralogy, which agrees with their albedo estimated from the Infrared Astronomical Satellite (IRAS) observations. However, according to the opinion of some researchers, Lutetia is of the C type, and, therefore, its mineralogy is of the low-temperature type. In turn, hydrosilicate formations have been found in some places on the surface of Vesta. Our observations also testify that at some relative phases of rotation (RP), the reflectance spectra of Lutetia and Vesta demonstrate features confirming the presence of hydrosilicates in the surface material. However, this fact can be reconciled with the magmatic nature of Lutetia and Vesta if the hydrated material was delivered to their surfaces by falling primitive bodies. Such small bodies are probably present everywhere in the main asteroid belt and can be the relicts of silicate–icy planetesimals from Jupiter's formation zone or the fragments of primitive-type asteroids. When interpreting the reflectance spectra of Lutetia and Vesta, we discuss the spectral classification by Tholen (1984) from the standpoint of its general importance for the estimation of the mineralogical type of the asteroids and the study of their origin and evolution.

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INTRODUCTION

The spectral (or multicolor) data available for a considerable number of asteroids from the main asteroid belt (MAB) allow their spectral classification to be fulfilled, i.e., the types or classes of minor planets with similar spectral properties to be distinguished. Since the spectral characteristics of asteroids (i.e., their spectra of diffuse reflection obtained under proper conditions) are directly connected with the chemical and mineralogical parameters of their surface material, the spectral type of each of them points to the predominant mineralogy. The latter, as is known (e.g., Korzhinskii, 1957; Deer et al., 1963), characterizes the physical and chemical conditions of the formation of the material of these bodies. To determine the mineralogical classes of asteroids, the taxonomical, more exactly, spectral classification by Tholen (1984; 1989) is currently in general use. It contains 14 classes of asteroids. The wide recognition of this classification is explained by the fact that it was developed starting from the statistical (cluster) approach with the correlation method of data analysis (the method of principal components or variables) and its physical sense is clear. It was fulfilled on the basis of the results of the eight-color photometric review of 589 asteroids (ECAS) in bands uniformly distributed in the range from 0.3 to 1.1 μm (Zellner et al., 1985). These data allowed for the reflectance spectra of asteroids to be approximated in a range whose boundaries coincide with the two strongest absorption bands of silicates: the electronic band of the oxygen–metal charge transfer (with a minimum at 0.2 μm) and the pyroxene–olivine band (with a minimum at 1.0 μm). As the theoretical and experimental studies showed, the most intense ultraviolet absorption band in the spectrum of diffuse reflection of the crumbled silicate material mainly depends on the oxidation degree, and its long-wavelength wing (its shape and extension) determines the slope and the shape of the reflectance spectra throughout the visible range (Loeffler et al., 1974; Burns, 1993). The 1-μm absorption band is the superposition of the absorption bands produced by the spin-allowed electron transitions in Fe^{2+} ions in the crystal fields of orthopyroxene (the band centered at 0.90 μm), clinopyroxene (at 1.0 μm), and olivine (at 1.01 μm). It characterizes the total content of the listed rock-forming minerals in the material (Adams, 1975). In the classification, the photometric bands near 0.2 and 1.0 μm correspond to two main components controlling 95% of the differences between the distinguished types of asteroids. It follows from the above that all of the classes of the considered classification are assigned on the basis of the shape of the reflectance spectra of the asteroids, and this classification is actually spectral. The albedo was used here as an auxiliary parameter only in individual cases when, for example, it was necessary to distinguish between the classes with very close spectral characteristics (M, E, and P) (Tholen, 1989). The mentioned properties of the classification make it possible to connect the distinguished spectral classes with different mineralogical types of solid material (Gaffey et al., 1989). As a practical application of the classification, the paper by Bell et al. (1989) can be considered. To describe the successive stages of the evolution of asteroids and the changes of their composition, the authors of that paper introduced superclasses containing several classes. They are the superclasses of primitive (including the classes D, P, C, K, and O), metamorphic (T and B + G + F), and magmatic (V, R, S, A, M, and E) asteroids. From the standpoint of evolution, the heliocentric distance distributions of both spectral classes and the superclasses of asteroids are important (Gradie and Tedesco, 1982). They demonstrate the continuous transition from magmatic to metamorphic and further to primitive asteroids with movement away from the Sun. An interesting feature of these dependences, which will be considered at the end of this paper, is the “spacious” character of the distribution of the C-type asteroids.

For comparison, we will also mention one of the recent taxonomic classifications of asteroids (Bus and Binzel, 2002b) based on the reflectance spectra of 1447 asteroids (Bus and Binzel, 2002a) and containing 26 classes. The further development of the “spectral” approach can be considered as an advantage of the new classification. Eleven out of the fourteen classes remained, and the additional classes and subclasses were introduced to characterize the reflectance spectra and, consequently, the asteroid mineralogy in more detail. However, its disadvantage is the grouping of magmatic classes M and E with the primitive class P (by the similarity of their reflectance spectra) into the joint class X, which creates problems for the interpretation of the evolutionary interconnection between different spectral classes of asteroids.

Thus, with accounting for the spectral classes of the considered asteroids 21 Lutetia and 4 Vesta (M and V class, respectively) (Tholen, 1989), they should be of a predominant magmatic mineralogy. This is confirmed by the high values of their IRAS albedo (Tedesco et al., 2004).

Asteroid Lutetia, the IRAS diameter of which is 95.76 km (Tedesco et al., 2004), is one of the objects for investigation in the *Rosetta* mission (ESA). This spacecraft is to approach Lutetia just in July 2010, which explains the increased interest in this asteroid and the extensive studies of this body. However, due to the ambiguous characteristics observed in this asteroid, many questions still wait to be answered. The rotation period of Lutetia is $8.^{h}172$ (Batrakov et al., 2000), and the shape of its lightcurve is irregular (Dotto et al., 1992; Michalowski, 1996). It is still unclear how to interpret the complicated lightcurve of the asteroid: by the extremely irregular shape of the body, by the albedo heterogeneities, or even by the duality or multiplicity of the system (see, e.g., Prokof’efa et al., 2006; Prokof’eva-Mikhailovskaya et al., 2007). One more open problem is the disagreement between the high-temperature type of Lutetia and the spectral features testifying to the presence of hydrated compounds on its surface, which was detected from the spectral data near the absorption band at 3.0 μm (Rivkin et al., 2000). Moreover, in the reflectance spectra of Lutetia, the absorption band of hydrosilicates at 0.44 μm (Busarev et al., 2004b; Lazzarin et al., 2004) and the unusual variations in the spectral continuum (Nedelcu et al., 2007; Busarev, 2008) were found. The complicated characteristics of this asteroid led to the suggestion that it had been mistakenly assigned to the M type and that it is actually a primitive object of the C type (see, e.g., Barucci et al., 2008). However, such a supposition contradicts the rather high value of the IRAS albedo of Lutetia, 0.22 (Tedesco et al., 2004).

Asteroid 4 Vesta is to be investigated during the *Dawn* mission (NASA). In 2011, this spacecraft is expected to return high-resolution images of the asteroid’s surface and other parameters, which will allow researchers to ascertain its surface structure in detail, to determine the chemical and mineralogical composition, and to make the available geochemical models more accurate. The albedo and the diameter of Vesta estimated before from the IRAS data are 0.42 and 468.30 km, respectively (Tedesco et al., 2004). The rotation period of the asteroid is $5.^{h}334$ (Batrakov et al., 2000). The magmatic origin of Vesta is confirmed by such facts as the discovery of solidified basalt lava flows with the Hubble Space Telescope (HST) (e.g., Thomas et al., 1997; Parker et al., 2002) and the detection of a group of asteroids, called vestoids, and their probable fragments—basalt HED meteorites (achondrites) (Binzel and Xu, 1993). However, from the spectral data near 3 μm, hydrosilicate formations were found at longitudes from 155°–195° on the surface of Vesta (Hasegawa et al., 2003). The authors of that study infer that hydrosilicates were delivered to the asteroid’s surface due to the collision with a primitive body of a carbonaceous chondrite composition. It is the largest impact crater near the southern pole of Vesta that can be the result of the oblique impact, having scattered the material of such a body throughout the surface of the asteroid (Hasegawa et al., 2003). Later, in the more thorough infrared (IR) studies, it was confirmed that the reflectance spectra of Vesta, corresponding to some longitudes and latitudes, contain signs of a weak absorption band near 3.0 μm (with a relative intensity of about 1%) (Rivkin et al., 2006).

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

Object	Date	UT, h m s	α, h m s	δ, degree, min of arc, s of arc	Δ, AU	*r*, AU	φ, degree	*V*, magnitude	ω; *L*, degree	*M*(*z*)	σ_1	σ_2	σ_3
16 Cyg B	2004 11 05	17 55 08	19 41 52	+50 31 00	–	–	–	6.2	–	1.221	–	–	–
21 Lutetia (1)	2004 11 05	23 48 27	02 32 55	+11 20 50	1.257	2.245	2.5	9.9	0.000	1.450	0.018	0.005	0.011
21 Lutetia (2)	2004 11 05	23 54 26	02 32 54	+11 20 50	1.257	2.245	2.5	9.9	0.012	1.488	0.018	0.003	0.014
21 Lutetia (3)	2004 11 06	00 00 41	02 32 54	+11 20 49	1.257	2.245	2.5	9.9	0.025	1.526	0.020	0.005	0.011
16 Cyg B	2004 11 07	17 50 05	19 41 52	+50 31 00	–	–	–	6.2	–	1.223	–	–	–
21 Lutetia (1)	2004 11 07	21 07 13	02 31 03	+11 15 06	1.263	2.249	3.3	10.0	0.545	1.300	0.037	0.011	0.016
21 Lutetia (2)	2004 11 07	21 13 25	02 31 02	+11 15 05	1.263	2.249	3.3	10.0	0.558	1.323	0.017	0.005	0.026
21 Lutetia (3)	2004 11 07	21 20 54	02 31 02	+11 15 05	1.263	2.249	3.3	10.0	0.573	2.062	0.013	0.007	0.016
21 Lutetia (4)	2004 11 07	21 26 57	02 31 02	+11 15 04	1.263	2.249	3.3	10.0	0.585	2.167	0.013	0.006	0.017
16 Cyg B (1)	2008 10 28	16 37 00	19 41 52	+50 31 00	–	–	–	6.2	–	1.123	–	–	–
16 Cyg B (2)	2008 10 28	17 59 30	19 41 52	+50 31 00	–	–	–	6.2	–	1.310	–	–	–
4 Vesta (1)	2008 10 28	23 24 05	02 33 22	+03 38 35	1.539	2.521	4.3	6.4	0.000; 203.9	1.676	0.036	0.011	0.023
4 Vesta (2)	2008 10 29	00 06 36	02 33 20	+03 38 28	1.539	2.521	4.3	6.4	0.133; 251.6	1.984	0.037	0.010	0.024
16 Cyg B	2008 10 29	18 29 30	19 41 52	+50 31 00	–	–	–	6.2	–	1.425	–	–	–
4 Vesta (1)	2008 10 29	23 28 49	02 32 22	+03 34 52	1.539	2.522	4.2	6.4	0.507; 26.5	1.740	0.033	0.009	0.029
4 Vesta (2)	2008 10 30	00 28 30	02 32 19	+03 34 43	1.539	2.522	4.2	6.4	0.694; 93.5	2.288	0.041	0.018	0.015
16 Cyg B	2008 10 30	18 35 30	19 41 52	+50 31 00	–	–	–	6.2	–	1.460	–	–	–
4 Vesta (1)	2008 10 30	21 35 12	02 31 26	+03 31 33	1.540	2.522	4.2	6.4	0.646; 76.2	1.369	0.017	0.010	0.019
4 Vesta (2)	2008 10 30	23 11 02	02 31 22	+03 31 18	1.540	2.522	4.2	6.4	0.945; 183.9	1.666	0.012	0.010	0.020
4 Vesta (3)	2008 10 31	00 24 19	02 31 19	+03 31 08	1.540	2.522	4.3	6.4	0.173; 266.2	1.302	0.033	0.016	0.024
HD 10307	2008 11 25	23 25 00	01 41 47	+42 36 48	–	–	–	4.9	–	1.432	–	–	–
21 Lutetia (1)	2008 11 26	01 19 01	04 32 38	+20 41 37	1.430	2.415	2.3	10.3	0.671	1.497	0.033	0.016	0.041
21 Lutetia (2)	2008 11 26	02 37 27	04 32 35	+20 41 33	1.431	2.415	2.3	10.3	0.831	2.128	0.031	0.010	0.031
HD 10307	2008 12 01	22 59 15	01 41 47	+42 36 48	–	–	–	4.9	–	1.422	–	–	–
21 Lutetia (1)	2008 12 02	00 00 57	04 26 00	+20 35 32	1.440	2.425	0.9	10.2	0.133	1.306	0.026	0.010	0.046
21 Lutetia (2)	2008 12 02	01 41 34	04 25 56	+20 35 27	1.440	2.425	0.9	10.2	0.338	1.857	0.067	0.011	0.060

Note: UT is universal time; α and δ are right ascension and declination, respectively; Δ and *r* are the geocentric and heliocentric distances, respectively; φ is the phase angle; *V* is the visible magnitude; ω is the relative phase of rotation; *L* is the longitude on Vesta calculated with the formula from the paper by Cochran and Vilas (1998); *M*(*z*) is the air mass; and the errors in the reflectance spectra of 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. In the brackets after the names of the asteroids, there are the numbers of their reflectance spectra obtained during one night and presented in the figures for the corresponding dates.

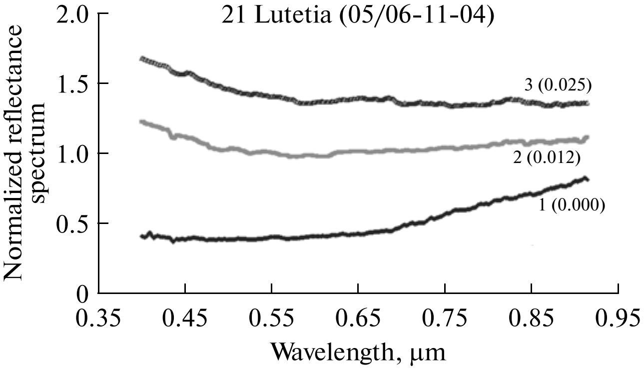

Fig. 1. The normalized (to the value at 0.55 μm) reflectance spectra of asteroid 21 Lutetia obtained on November 5–6, 2004. Spectra *1–3* are shown in chronological order and shifted relative to each other for convenience. The relative phase of the asteroid's rotation is given in brackets after the spectrum number. The rotation phase of the very first spectrum is assumed to be zero.

This means that many places on the surface of Vesta are speckled with hydrated material.

In previous studies, we considered the similar "scenario" that the delivery of hydrosilicate compounds of the carbonaceous chondrite type onto some asteroids of magmatic classes occurred during collisions with small primitive bodies (Busarev, 1998; 2000; 2002). Now we will show that our observational data on Lutetia and Vesta confirm the analogous interpretation of the source of hydrosilicates on their surfaces.

OBSERVATIONAL AND LABORATORY DATA

Even over the course of about 40 years, the spectrophotometric method (recently, CCD spectrometry) in the visible and near-IR ranges (from 0.35 to 1.1 μm) has been successfully applied to estimate the composition of the material of solid atmosphereless celestial bodies with the use of ground-based telescopes (Adams and McCord, 1970; McCord and Adams, 1975; Busarev, 1999). The limits of this spectral range are determined by the boundaries of the most extended and transparent "window" of the terrestrial atmosphere (see, e.g., Walker, 1987). The considered method of estimating the composition of the material of solid celestial bodies is comprised of two stages. The first one is performed with the use of a telescope with a spectrograph; it includes the registration of the spectra of the solar radiation diffusely reflected by the solid body and the spectra of one or more stars, solar analogs, close to this body during the observations. Such comparison stars are used as "substitutes" for the Sun and for taking into account the spectral atmospheric transparency. The number of solar analogs properly fitting by photometric parameters is relatively small, only about two or three tens (Hardorp, 1980; Cayrel de Strobel, 1996; Glushneva et al., 2000). Moreover, only those stars from this list which show no variability are selected for being used as spectrophotometric standards. The observations are performed with the differential spectrophotometry method, which makes it possible to account for the effects of the air mass difference and the spectral transparency of the terrestrial atmosphere and to eliminate them from the obtained data (see, e.g., Kharitonov et al., 1988). The first stage terminates in the calculations of the reflectance spectra of the solid body (an asteroid) with the use of the measured spectra and the spectra of one or more (for comparison) stars, solar analogs (Busarev, 1999; Busarev et al., 2007). The spectra of Lutetia and Vesta were acquired in 2004–2008. We used the 1.25-m telescope of the SAI (Sternberg Astronomical Institute) Crimean Observatory coupled with a CCD spectrograph operating in the range from 0.39 to 0.91 μm with a spectral resolution of about 8 Å. Due to the design of the spectrograph, the spectrum of the object is sequentially recorded by two portions (0.39–0.71 and 0.65–0.91 μm), which are joined during the processing. As a rule, this procedure introduces no considerable error, because the spectrum portions are recorded with a small time interval in between (about 10–20 min depending on the exposure time). In the center of the range of 0.45–0.70 μm, the mean-root-square error of the calculated reflectance spectra was less than 1–2%, while it was different at its blue and red boundaries (depending on the observational conditions and the brightness of the objects); but, as a rule, it did not exceed 5–7%. To eliminate the noise component appearing from the terrestrial atmosphere and from the dividing of the source spectrum of the object by that of the solar analog (when approximating the reflectance spectrum), the smoothing of the reflectance spectrum by the "running mean" method and the polynomial extrapolation of the spectrum continuum near the blue and red boundaries were used. During different observational periods, the same stars, solar analogs (HD 10307 and 16 Cyg B), were used for calculating the reflectance spectra and determining the spectral transparency of the atmosphere. The conditions of the observations of the asteroids and the star analogs and the errors of the spectra are listed in the table; the normalized reflectance spectra of Lutetia and Vesta are displayed in Figs. 1–7.

The second stage in the analysis of the spectral characteristics and the estimation of the composition of the material of solid atmosphereless celestial bodies contains the comparison of their reflectance spectra with the laboratory reflectance spectra of their probable analog samples. The analogs of the asteroid material are meteorites, as the probable asteroid fragments, and the terrestrial rocks and minerals. Assuming that the predominant composition of the regolith of Lutetia and Vesta is known from the specified magmatic classes (it can be a set of pyroxenes, olivines, and other high-temperature minerals and compounds) (Gaffey et al., 1989; 2002) and that the spectral characteristics of the listed minerals are also known, let us

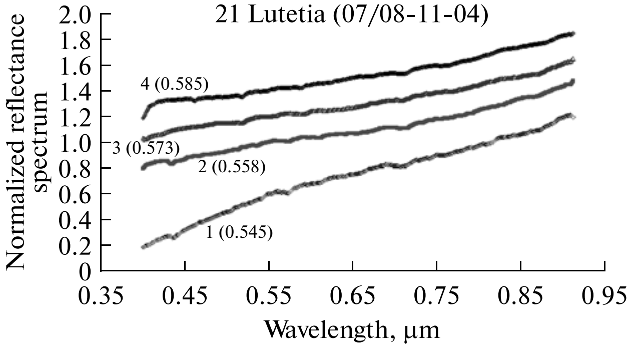

Fig. 2. The normalized (to the value at 0.55 μm) reflectance spectra of asteroid 21 Lutetia obtained on November 7–8, 2004. Spectra *1–4* are shown in chronological order and shifted relative to each other for convenience.

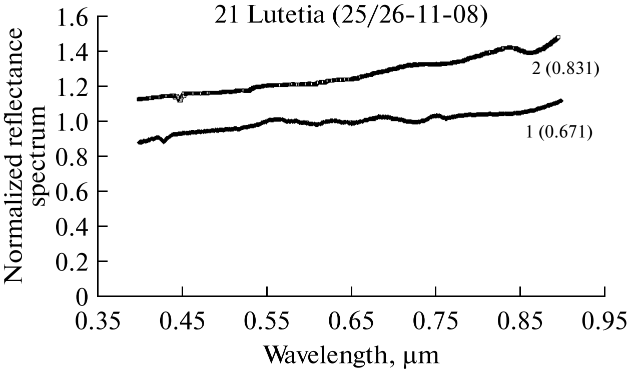

Fig. 3. The normalized (to the value at 0.55 μm) reflectance spectra of asteroid 21 Lutetia obtained on November 25–26, 2008. Spectra *1* and *2* are shown in chronological order and shifted relative to each other for convenience.

consider the spectral properties of carbonaceous chondrites and terrestrial hydrosilicates that can demonstrate themselves against "the background" of the material with high-temperature mineralogy.

We previously performed laboratory studies of the reflectance spectra of carbonaceous chondrites of the CI and CM groups as the most primitive and hydrated meteorites (Busarev and Taran, 2002). In particular, the CI-group carbonaceous chondrites almost entirely consist of a mixture of fine (submicron sized) particles of low-temperature hydrosilicates (up to 90 wt %) containing up to 17–22 wt % of bound water (Dodd, 1981; Jarosewich, 1990) and up to 6 wt % of carbonaceous amorphous material, the so-call "matrix" (Hayes, 1967). Figure 8 taken from our previous paper (Busarev and Taran, 2002) shows the reflectance spectra of four crumbled samples of carbonaceous chondrites. It is seen from the plot that the common feature of the reflectance spectra of all of these samples is the presence of a wide absorption band in the range of 500–1000 nm centered at 0.75–0.80 μm. It is caused by the electronic transfer of a charge $Fe^{2+} \longrightarrow Fe^{3+}$ in the hydrated silicate material (Platonov, 1976; Bakhtin, 1985; Burns, 1993). In these spectra, the ultraviolet edge of absorption is observed at 380 nm, since the measurements are made in the terrestrial atmosphere. In a vacuum, the spectra of carbonaceous chondrites show the edge of absorption at shorter wavelengths (Wagner et al., 1987). Because of this, it is worth noting that the shape of the reflectance spectrum of carbonaceous chondrites is generally concave throughout the visible range. A similar shape is also typical of the reflectance spectra of serpentines. Figure 9 taken from our other paper (Busarev et al., 2004a) displays the diffuse reflectance spectra of the crumbled samples of terrestrial serpentines of lizardite–chrysotile form. The latter are produced at the initial, mostly low-temperature, stage of the formation of hydrosilicates from the antecedent minerals or rocks (Deer et al., 1963). It is seen from the plot that a rather strong absorption band in the range of 0.40–0.49 μm centered at 0.44–0.45 μm is characteristic of this kind of serpentines. As has been found in the Mossbauer studies of these samples, the equivalent width of the absorption band at 0.44–0.45 μm closely correlates with the content of Fe^{3+} (Busarev et al., 2008). The additional indicators of the oxidized material are the absorption bands centered at 0.60 and 0.67 μm; they were discovered 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). Let us show that the listed spectral features of hydrated, highly oxidized, or oxidized compounds are present in the reflectance spectra of Lutetia and Vesta.

DISCUSSION OF THE OBSERVATIONAL RESULTS

Lutetia

Figure 1 shows the normalized reflectance spectra of Lutetia obtained at close values of the relative phase of rotation (the RP is 0.000–0.025; the RP of the very first spectrum is assumed to be the zero RP) on November 5–6, 2004. It is seen that their shape is concave, typical of primitive BGF asteroids, close to the C-type asteroids (Tholen, 1989). As has been already noted, such a shape of the reflectance spectra in the visible range is characteristic of hydrosilicate-enriched carbonaceous chondrites and terrestrial hydrosilicates (see Figs. 8, 9), which is indicative of the presence of iron ions Fe^{2+} and Fe^{3+} in the material and their electron interaction. Moreover, in the reflectance spectra of Lutetia, there is one more indicator of the Fe^{3+} content—a weak absorption band at 0.43–0.45 μm (Fig. 1). The essentially different shape with a substantial positive slope, characteristic of D-type asteroids (Tholen, 1989), was demonstrated by the reflectance spectra of Lutetia obtained on November 7–8, 2004 (Fig. 2).

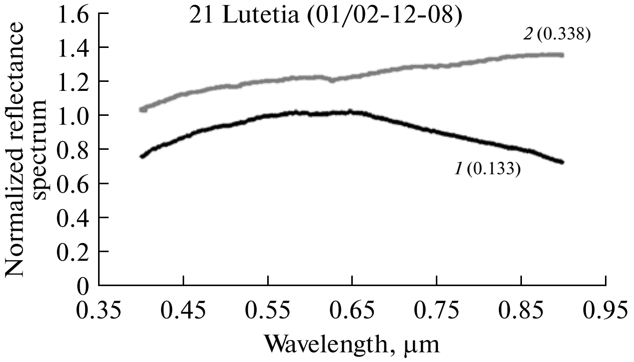

Fig. 4. The normalized (to the value at 0.55 μm) reflectance spectra of asteroid 21 Lutetia obtained on December 1–2, 2008. Spectra *1* and *2* are shown in chronological order and shifted relative to each other for convenience.

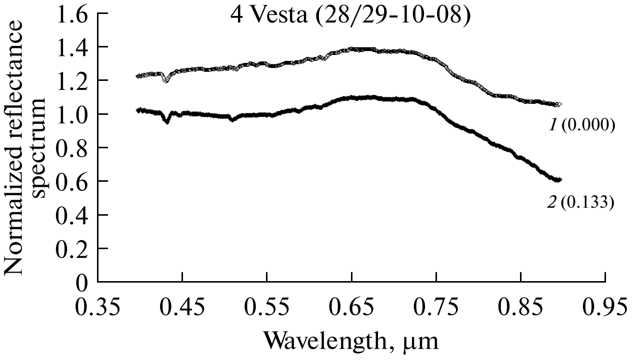

Fig. 5. The normalized (to the value at 0.55 μm) reflectance spectra of asteroid 4 Vesta obtained on October 28–29, 2008. Spectra *1* and *2* are shown in chronological order and shifted relative to each other for convenience. The relative phase of the asteroid's rotation is given in brackets after the spectrum number. The rotation phase of the very first spectrum is assumed to be zero.

They correspond to its opposite side (the RP is 0.545–0.585). Besides the weak signs of the absorption band at 0.43–0.45 μm and the absorption feature of unknown origin at 0.71–0.72 μm, these spectra contain no common features. The reflectance spectra of Lutetia obtained at the other RP values (0.671–0.831) on November 25–26, 2008 show a small positive slope and a slightly concave shape (Fig. 3). Such a shape of the reflectance spectra is typical of C-type asteroids (Tholen, 1989). Finally, the shape of the reflectance spectra of Lutetia obtained on December 1–2, 2008 (Fig. 4) is characteristic of S-type (spectrum *1*, the RP is 0.133) and M-type asteroids (spectrum *2*, the RP is 0.338) (Tholen, 1989). In this plot, the clear features of the pyroxene–olivine absorption band at 1.0 μm typical of S-type asteroids are seen in spectrum *1* and the weak band of pyroxenes at 0.51 μ (Platonov, 1976); the somewhat stronger absorption band of oxidized metallic compounds (Hiroi et al., 1996) are observed in spectrum *2*. It is also worth stressing that the reflectance spectra shown in the successive plots of Figs. 1–4 characterize the approximately opposite sides of the asteroid (according to the specified RP values). Thus, the reflectance spectra of Lutetia presented here cover the whole period of its rotation and testify to the substantial variability of the spectral characteristics, which correspond to different (C–G, D, or M–S) spectral classes of asteroids at different rotational phases. Similar variations in the reflectance spectra of Lutetia in the visible range were also observed during its opposition in March 2006 (Nedelcu et al., 2007; Busarev, 2008). They can be considered as a results of the changes in the average composition of the material of Lutetia from hydrosilicates and hydrocarbons to high-temperature minerals and/or metallic compounds. The terrestrial collection of meteorites already contains a sample of the material of this kind: this is the shock breccia Kaidun presenting a "gathering" of extremely different materials (Ivanov et al., 1998; Zolensky and Ivanov, 2003; Bischoff et al., 2006). As the authors of the listed papers note, Kaidun could be a fragment of the surface of the parent body, which experienced intense collisional evolution when moving from the MAB periphery to the Earth's orbit.

Contrary to the Kaidun meteorite, Lutetia is relatively large, but can also be a fragment of a larger body. According to the current paradigm (Bell et al., 1989), Lutetia, as one of the M-type asteroids, can be a part of the metallic core of a differentiated parent body. However, during its lifetime, Lutetia probably has not substantially changed its heliocentric distance, since it is located at the internal edge of the distribution of the known M-type asteroids in the Solar System (Gradie and Tedesco, 1982). Because of this, two versions of the interpretation of the rather heterogeneous composition of the material of Lutetia are possible. The first one is that it is an "intermediate" fragment of the parent body broken off at the boundary of its metallic core and silicate (or even hydrosilicate) mantle and preserving the material of these different mantles. In this case, Lutetia should consist of two parts different in composition: predominantly metallic and silicate (or hydrosilicate). Probably, the reflectance spectra of Lutetia (Figs. 1–4) characterizing its different sides confirm such differences. The other version of the interpretation of the heterogeneous properties observed on the surface of Lutetia is connected with the probability of the "delivery" of atypical (if its M type is approved) hydrated and/or highly oxidized compounds onto its surface during the falls of primitive bodies with a carbon-chondrite composition enriched with hydrosilicates. This scenario was earlier suggested for the interpretation of the analogous properties observed on the surface of the other asteroids of the magmatic types (Busarev, 1998; 2000; 2002). For the sake of completeness, one more result of the

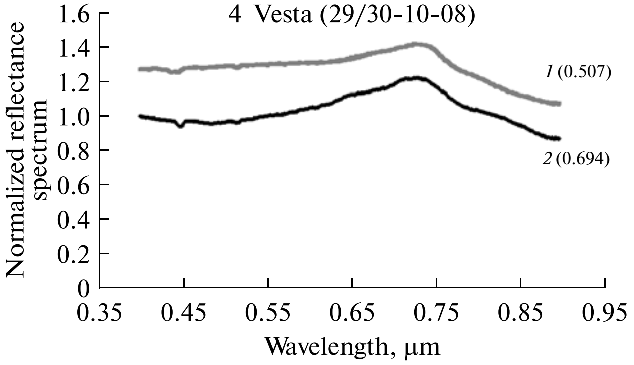

Fig. 6. The normalized (to the value at 0.55 μm) reflectance spectra of asteroid 4 Vesta obtained on October 29–30, 2008. Spectra *1* and *2* are shown in chronological order and shifted relative to each other for convenience.

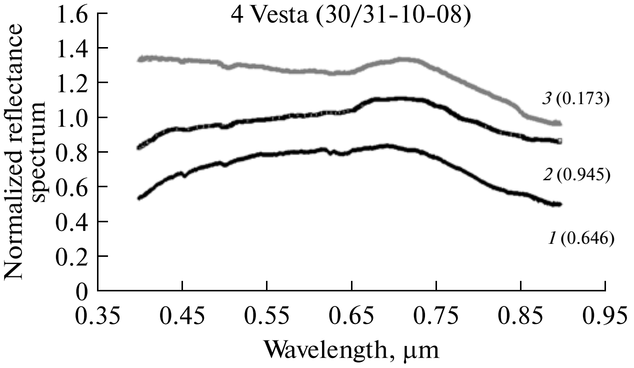

Fig. 7. The normalized (to the value at 0.55 μm) reflectance spectra of asteroid 4 Vesta obtained on October 30–31, 2008. Spectra *1–3* are shown in chronological order and shifted relative to each other for convenience.

experiments should be mentioned here. It was obtained with a pulsing laser in the modeling of the melting and evaporation of the silicate material during the meteorite impact. The idea of such a modeling for studying the transformation of the physical and chemical composition of the material in the meteorite impact (under typical velocities of the impacts varying from units to tens of km/s) was for the first time suggested and realized by our specialists (Gerasimov et al., 1999; Managadze, 2009). The analysis of the composition of the successive layers in the impact condensate formed during the laser-induced evaporation of the iron-containing silicates in the helium atmosphere showed that together with the decrease of the Fe^{2+} concentration, the content of Fe^{3+} rather than only Fe^0 increases (Yakovlev et al., 2009). The authors of the mentioned paper conclude that the chemical disproportionation of bivalent iron takes place in the natural impact processes on atmosphereless celestial bodies, and Fe^{2+} is transformed into Fe^0 and Fe^{3+} under the mean ratios $Fe^0 : Fe^{2+} : Fe^{3+} = 1.2 : 1.9 : 0.7$ (this experimental result was confirmed in the study of the impact condensate in the lunar-regolith samples returned by the *Luna-16* spacecraft). However, from these ratios, it is seen that the impact process still has a predominantly reducing character and the long impact alteration cannot lead to the prevalence of the trivalent iron above the other iron forms. Therefore, if the reflectance spectrum of the asteroid demonstrates the features typical of one valent state of iron, we may suggest that these features characterize the initial composition of the asteroid material and that they are not the consequence of the impact processes.

Vesta

The reflectance spectra of Vesta (Figs. 5–7) were also obtained under different values of its relative RP (the RP of the very first spectrum is assumed to be the zero RP) and, consequently, under different longitudes of the sub-Earth point. The longitudes of Vesta for the mean moments of the recording of its spectra were calculated with the formula taken from the paper by Cochran and Vilas (1998) (see table). Reflectance spectra *1* and *2* shown in Fig. 5 were obtained on October 28–29, 2008 (the RP is 0.000 and 0.133). Their most noticeable spectral feature is the short-wavelength wing of the 0.90-μm absorption band of orthopyroxenes caused by the spin-allowed electron transitions in Fe^{2+} ions being in the M2 positions (Platonov, 1976). This interpretation of the 0.90-μm absorption band is confirmed by the presence of weaker absorption bands of pyroxenes at 0.51 μm induced by the spin-forbidden transitions in Fe^{2+} ions (Platonov, 1976). The significant intensity of the absorption band of pyroxenes at 0.90 μm (especially in spectrum *2*) shows that the mineralogical composition of the surface of Vesta is mostly of the high-temperature type. At the same time, the spectra contain weak absorption bands of Fe^{3+} at 0.43 μm with a relative intensity of 5–7% (Busarev et al., 2008). In the range of 0.40–0.65 μm, the differences in the spectrum continuum are also observed: its shape changes from flat (curve *1*) to slightly curved (curve *2*). Since the latter feature is present in several reflectance spectra of Vesta, its interpretation will be considered at the end of this section. Two more reflectance spectra were obtained at the asteroid's RP 0.507 and 0.694 on October 29–30, 2008 (Fig. 6). Their shape is similar to that of the previously considered spectra. Some peculiarities are the sharper maximum at 0.73 μm, the weaker (~3%–4%) absorption bands of Fe^{3+} slightly shifted to 0.44 μm, and the weak band of pyroxenes at 0.51 μm. Finally, three last reflectance spectra of Vesta were acquired on October 30–31, 2008 (the RP is 0.646, 0.945, and 0.173) (Fig. 7). They attract attention by a rather sharp change in the continuum shape when moving from spectrum *2* to spectrum *3*, although the RP values and the shape of these spectra are close to those of spectra *1* and *2* in Fig. 5. Probably, spectra *2* and *3* of Fig. 7

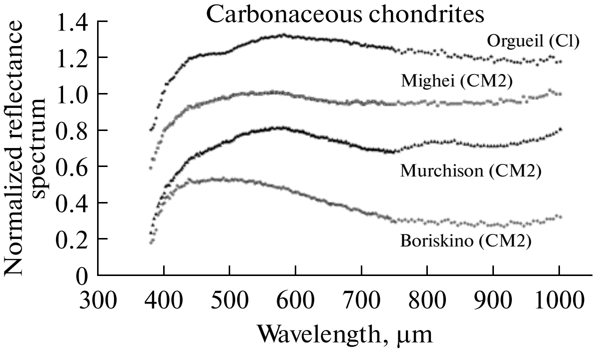

Fig. 8. The normalized (to the value at 550 nm) laboratory spectra of diffuse reflectance for four crashed samples (the particle size <0.25 mm) of carbonaceous chondrites (Busarev and Taran, 2002). The spectra are shifted relative to each other in the ordinates by the same distance. The classes of carbonaceous chondrites are shown in brackets after the names of the samples.

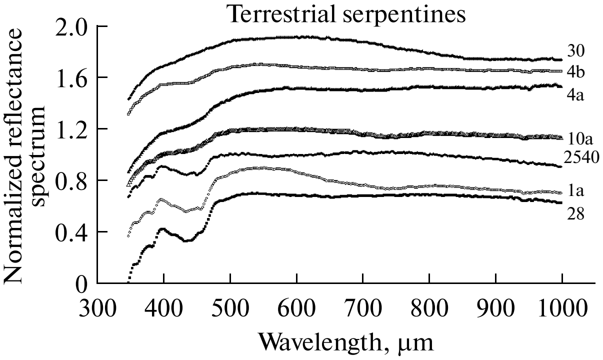

Fig. 9. The normalized (to the value at 550 nm) laboratory spectra of diffuse reflectance for seven crashed samples (the particle size <0.25 mm) of terrestrial serpentines (Busarev et al., 2004a). The spectra are shifted relative to each other in the ordinates by the same distance. Their order (from the top) corresponds to the increasing content of Fe^{3+} according to the Mossbauer data (Busarev et al., 2008), which correlates with the intensity of the absorption band centered at 440–460 nm. The numbers of the samples are shown next to the spectra.

more exactly characterize the transition boundary between different formations on the surface of Vesta than spectra *1* and *2* of Fig. 5 do. Moreover, it is near Vesta's longitudes of 155°–195°, corresponding to spectra *1* (Fig. 5) and *2* (Fig. 7) (see table), that Japanese researchers found hydrosilicates from the IR data at 3.0 μm (Hasegawa et al., 2003). In Fig. 7, the reflectance spectra show the same main properties as those of the previously considered spectra of the asteroid. Some additional features are the weak absorption bands of pyroxenes at 0.51 μm (Platonov, 1976) and, probably, of oxidized metallic compounds at 0.64 μm (Hiroi et al., 1996).

As has been noted, a common feature of spectra *2* in Fig. 5 (the RP is 0.133), *2* in Fig. 6 (the RP is 0.694), and *3* in Fig. 7 (the RP is 0.173) is their concave shape in the range of 0.40–0.70 μm. The first and last spectra were obtained at close values of the RP, while the second one corresponds to the opposite side of the asteroid. First of all, this means that the same large detail was first on the left, and then on the right of the visible side of Vesta's surface. Second, the material of the considered detail included hydrosilicates, which is probably confirmed by the concave shape of the reflectance spectra listed.

After a short description of the reflectance spectra of Vesta considered here, we will give their general interpretation. The obtained spectral characteristics of this asteroid generally agree with the analogous data of other authors (e.g., McCord et al., 1970; McFadden et al., 1977; Gaffey, 1997; Golubeva and Shestopalov, 1997). The average reflectance spectrum of Vesta in the visible and near-IR ranges has turned out to be identical to that of calcium pyroxene with the composition $Fs_{46}Wo_8$ (that means 46 and 8 mol % of Fe and Ca, respectively) (Gaffey, 1997). The specified composition was determined from the empirical dependence of the relation between the intensities and the position of pyroxene absorption bands at 0.90 and 2.00 μm (Adams, 1974; Gaffey, 1984). Such a composition of pyroxene is also typical of the meteorite family of eucrites, howardits, and diogenits (HED) belonging to basalt achondrites (see, e.g., Duke and Silver, 1967; Drake, 1979). The parent bodies of these magmatic meteorites can be Vesta and/or kilometer-sized asteroids, "vestoids," found between the orbit of Vesta and the 3 : 1 resonance orbit with Jupiter (Binzel and Xu, 1993). In addition, several vestoid asteroids were identified among the asteroids approaching the Earth (Cruikshank et al., 1991). This means that they can be thrown away from the main asteroid belt if they occur on the mentioned resonance orbit. The modeling of the origin of such a huge impact crater found by the HST near the southern pole of Vesta (Thomas et al., 1997) showed that this impact event could induce the appearance of both vestoid asteroids and achondrite meteorites falling onto the Earth (Asphaug, 1997). Thus, all of the listed observational facts and the results of the modeling of the thermal evolution of Vesta (see, e.g., Kevin and Drake, 1997) confirm the formation of a high-temperature magmatic ocean on its surface in the past and the consequent forming of the basalt mantle, the fragments of which are HED meteorites. In this case, the presence of low-temperature hydrosilicates on the surface of Vesta looks strange, since they should have become degraded (if the initial composition of the asteroid is assumed to be carbon chondrite) at high temperatures of magma (~1000°C or higher).

ON THE POSSIBLE MECHANISM OF THE APPEARANCE OF HYDROSILICATES ON THE SURFACE OF LUTETIA, VESTA, AND SOME OTHER MAGMATIC CELESTIAL BODIES

During the postmagmatic period, OH-containing compounds could appear on the surface of Lutetia and Vesta either under the influence of cosmogonic factors (specifically, under the chemical interaction of solar-wind protons with oxygen contained in silicate rocks) (Starukhina, 2001) or be delivered there during impact events. We prefer the second scenario in the interpretation of the spectral features testifying to the presence of hydrosilicates of the surface of Lutetia, Vesta, and other magmatic bodies. The reasons are the following.

From the results of the spectral studies of the known M-type asteroids fulfilled at the diagnostic absorption band of H_2O/OH in the 3-μm range, it was found that only 35% of such bodies are hydrated (Rivkin et al., 2000). It is evident that the portion of the hydrated bodies would be close to 100% if the OH compounds appeared on the surface of M-type asteroids under the influence of such a common factor as the solar wind.

To search for and detect the spectral (including albedo) heterogeneities on the surface of asteroids and other atmosphereless bodies of the Solar System, we developed the special spectral frequency method (Busarev et al., 2007). It is a combination of the before-known spectral and frequency astrophysical methods of the investigations of celestial bodies. With this method applied, first, surface features with sizes less than the diameter of the rotating celestial body can be detected from the short-term variations of its spectral characteristics, and, second, the physical and chemical properties of these features can be determined. The considered method is based on the registering of a rather long set of the spectra of the specified celestial body during the interval corresponding to at least several periods of its rotation. The acquired data are analyzed in order to identify any frequently occurring spectral feature. Then, the series of values of the selected spectral parameter arranged according to the change in the rotation phase of the body are calculated, and their frequency analysis is performed. For example, the parameter characterizing the mineralogical absorption band in the reflectance spectrum of a solid celestial body is its equivalent width (W). To obtain information about the distribution of hydrated and/or highly oxidized silicates on Lutetia and Vesta, we selected the absorption band of Fe^{3+} at 0.44 μm in their reflectance spectra (Busarev et al., 2008). From the results of the frequency analysis of the equivalent width W of this absorption band in 40 reflectance spectra of Lutetia, the spots of hydrated and/or highly oxidized compounds with sizes ranging from 3 to 70 km were found on the surface of the asteroid (Prokof'eva et al., 2005). The analogous analysis of the variations in the W value of the same band in 91 reflectance spectra of Vesta yielded a similar result and showed that more than 50% of the corresponding features on the surface of the asteroid are from 13 to 50 km in size (Prokof'eva–Mikhailovskaya et al., 2008). It is interesting to note that the obtained maximum in the size distribution of hydrated and/or highly oxidized compounds on the surface of Lutetia and Vesta corresponds to the maximum in the distribution of the impact craters on the surface of the Moon, asteroids, and other atmosphereless celestial bodies (Ivanov et al., 1999; Schmedemann et al., 2009).

The problem with the interpretation of the spectral signs of hydrosilicates analogous to that we consider here has recently appeared in the studies of the Moon. The imaging of the lunar surface in the range of 2.8–3.0 μm fulfilled from the Indian *Chandrayaan 1* spacecraft allowed for the presence of hydrosilicates (by their absorption band in the reflectance spectrum of the lunar surface) to be detected in the polar regions and near some relatively young impact craters (Pieters et al., 2009). From the absence of a correlation between the absorption band of hydrosilicates and the hydrogen content determined from the neutron data in regions illuminated by the Sun, the authors of that paper concluded that these compounds were formed and accumulated due to other processes on the surface.

As has been already noted, the most intense processes on the surface of atmosphereless celestial bodies are the impact alteration (crumbling, melting, evaporation, condensation, etc.) of their material and the delivery of new material, including hydrated, during the falls of bodies. It is worth mentioning here the experimental result that is important for the interpretation of the consequences of significant meteorite impacts. In these experiments, the serpentine samples (with a bound water content of 12.5%) sealed into a metallic capsule were subjected to a blow with metallic plates accelerated to high velocities (about several km/s) by an explosion (Rivkin et al., 2003). The subsequent measurements of the reflectance spectra of the crumbled samples (the particle size is less than 125 μm) of the initial material and the material subjected to impact loading (20–40 GPa) showed that the serpentine that experienced an impact almost completely preserved its spectral properties (the position and the intensity of the absorption bands of OH and H_2O at 3.0 μm). Thus, if serpentines are not heated to high temperatures during impact events (at some distances from the impact epicenter), we may say that they "survive." In this connection, it should be stressed that such conditions are typical of the majority of colliding bodies. In the epicenters of the impacts of meteorites and micrometeorites with orbital velocities, the material is subjected to the complex effect of high pressure and temperature (up to several thousands of degrees), which leads to its melting, evaporation, and condensation. However, as experimental modeling shows, even if the material experienced such extreme conditions, the impact condensate can preserve not only the oxides and hydrates of metals, but also volatiles containing hydrogen, carbon, sulfur, phosphorus, and chlorine, which were in the initial sample (Gerasimov et al., 2002; Yakovlev et al., 2009).

As follows from the analytical and numerical analyses, the dynamical chaotization of the MAB occurred at the protoplanetary stage of the evolution of the Solar System due to the resonance–gravitational and gravitational disturbances from the growing Jupiter and large protoplanetary bodies coming to the MAB from the zones of Jupiter or the terrestrial planets (Safronov, 1969; Davis et al., 1979; 1985; Safronov and Ziglina, 1991; Petit et al., 2001; Magni and Coradini, 2004; Bottke et al., 2005; O'Brien et al., 2007). These bodies, moving along the orbits with large eccentricities, could repeatedly penetrate to the MAB and collide with the parent bodies of asteroids. Due to these intense gravitational and impact interactions of the bodies everywhere in the MAB, the relative velocity of the asteroids substantially increases, from hundreds of m/s to its current value of ~5 km/s. Moreover, the material of the colliding bodies, which had the predominantly silicate–icy or carbon chondrite composition at the protoplanetary stage of the evolution (at least, their external envelopes), was crushed, mixed, and scattered. Probably, the dust component of such a crashed material was rather quickly removed from the MAB by the influence of some physical factors (see, e.g., Busarev, 2004). However, larger fragments with typically meteoroid asteroid sizes (from tens of meters to one kilometer) having substantially larger inertia could remain as relicts at those heliocentric distances where they had been formed if they did not come to the resonance-to-Jupiter orbits and were not removed from the MAB. Probably, the population of such small primitive bodies—the fragments of the parent bodies of asteroids and the protoplanetary bodies that collided with them—still compose the MAB at all of the heliocentric distances. Therefore, the falls of relatively small bodies of a primitive composition onto asteroids of any composition could occur throughout the history of the MAB. Such a hypothesis was actually suggested in our previous studies (Busarev, 1998; 2000; 2002) for the interpretation of the spectral signs of the presence of hydrosilicates on some asteroids of the magmatic types. This supposition can be independently confirmed by the discovery of several small bodies belonging to the MAB, which "manifested" their internal ice composition probably due to recent collisions (Hsieh and Jewitt, 2006). As has been already noted, this hypothesis can be also supported by the "spacious" character of the distribution of the known C-type asteroids (with assumed carbonaceous chondrite mineralogy) that is opposite to the distributions of asteroids of other types having better defined localization in the MAB through the heliocentric distances (Gradie and Tedesco, 1982).

Starting from the results and concepts presented here, the discovery of hydrosilicates on Lutetia, Vesta, and many other bodies of magmatic origin can be considered as natural rather than random, since it agrees with the evolution of these bodies and the history of the Solar System.

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