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Characteristic Features in the Spectra of Europa, Ganymede, and Callisto

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Abstract—The results of ground-based spectrophotometry of the icy Galilean satellites of Jupiter—Europa, Ganymede, and Callisto—are discussed. The observations were carried out in the 0.39–0.92 μm range with the use of the CCD spectrometer mounted on the 1.25-m telescope of the Crimean laboratory of the Sternberg Astronomical Institute in March 2004. It is noted that the calculated reflectance spectra of the satellites mainly agree with the analogous data of the earlier ground-based observations and investigations in the *Voyager* and *Galileo* space missions. The present study was aimed at identifying new weak absorption bands (with the relative intensity of ~3–5%) in the reflectance spectra of these bodies with laboratory measurements (Landau et al., 1962; Ramaprasad et al., 1978; Burns, 1993; Busarev et al., 2008). It has been ascertained that the spectra of all of the considered objects contain weak absorption bands of molecular oxygen adsorbed into water ice, which is apparently caused by the radiative implantation of O^+ ions into the surface material of the satellites in the magnetosphere of Jupiter. At the same time, spectral features of iron of different valence (Fe^{2+} and Fe^{3+}) values typical of hydrated silicates were detected on Ganymede and Callisto, while probable indications of methane of presumably endogenous origin, adsorbed into water ice, were found on Europa. The reflectance spectra of the icy Galilean satellites were compared to the reflectance spectra of the asteroids 51 Nemausa (C-class) and 92 Undina (X-class).

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INTRODUCTION

Among 63 satellites of Jupiter that are known to date, the Galilean satellites—Io, Europa, Ganymede, and Callisto—are the largest and best known. The latter three of them are called icy because of the composition of their surface material. An interesting characteristic of these satellites is the simultaneous decrease of the geometric albedo (ρ_v) and the density ρ with the distance from Jupiter: from $p_v = 0.68$ and $\rho = 3.01$ for Europa to $p_v = 0.44$, $\rho = 1.94$ for Ganymede and to $p_v = 0.19$, $\rho = 1.83$ for Callisto (http://nssdc.gsfc.nasa.gov/planetary/factsheet/joviansatfact.html). The presence of water ice in these bodies was ascertained even in the early ground-based spectrophotometric and infrared (IR) observations (Moroz, 1965; Johnson and McCord, 1970; 1971; Pilcher et al., 1972). Signs of the presence of internal water oceans heated by tidal disturbances from Jupiter, rather than only the ice crust, were found during the *Voyager* (NASA, from the late 1970s to the mid-1980s) and *Galileo* (NASA, from 1995 to 2003) space missions. Specifically, from the *Galileo* images taken with a resolution of 54 m, the signs of the global renewal of the surface were discovered on Europa: the crater density is extremely low for the body lacking an atmosphere, and "iceberg"-type formations that have recently moved over the surface (in the geological time scale) are present.

Since the Galilean satellites were formed together with Jupiter beyond the water-ice-condensation boundary, their common property is the substantial enrichment with water and other volatiles (CO_2, H_2S, NH_3) (see, e.g., Safronov, 1969; Anders and Grevesse, 1989; Lissauer, 2005; Lunine, 2006; Kuskov et al., 2009). One of the confirmations of this property is the composition of the surface material of Europa (more than 90% of water ice), Ganymede (not less than 50% of water ice), and Callisto (less than 10% of water ice) estimated by their reflectance spectra (McCord et al., 1997b). The analogous modeling showed that the non-icy materials of Ganymede and Callisto are similar to carbonaceous chondrites from their spectral characteristics, though they may contain more organics and hydrosilicates like serpentine (Calvin and Clark, 1989). (This circumstance is considered in the present paper in more detail.) A significant factor is also a general process of maturation of the surface material of celestial bodies lacking an atmosphere under space conditions. By the cratering degree, the surface of Europa is youngest, and its age is estimated at about 50 Myr (Zahnle et al., 2003). At the same time, the surface of Ganymede is older than that of Europa, and the surface of Callisto is older that that of Ganymede (Passey and Shoemaker, 1982; Greenberg, 2010). It is worth noting that, since the meteoroid flux is gravitationally focused by Jupiter, its density and intensity in the zone of the Jovian satellites can be the same or

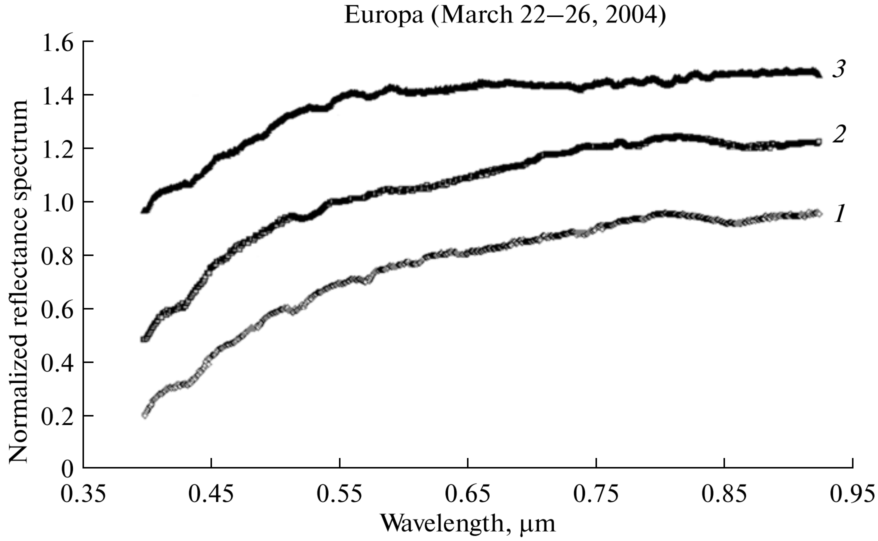

Fig. 1. The reflectance spectra of the Jovian satellite Europa (*1–3*) obtained on March 22–26, 2004. They are smoothed, normalized (to the value at $\lambda = 0.5503$ μm), and vertically shifted for comparison. The recording time and the errors of the reflectance spectra are listed in Table 1. Spectra *1, 2*, and *3* correspond to the leading, trailing, and leading sides of the satellite, respectively.

even larger than those in the Main asteroid belt (Busarev et al., 2007b).

Thorough spectral observations showed that water ice is found in crystalline and amorphous forms on the icy Galilean satellites (e.g., Dalton et al., 2010). Crystalline ice differs from amorphous one by the presence of a narrow absorption band at 1.65 μm and the Fresnel maximum at 3.1 μm in its spectrum; the latter is considered to be an indication of the crystalline structure of the material in the upper layer several microns thick (Fink and Larson, 1975; Dalton et al., 2010). As it turned out, two competitive processes take place on the surfaces of the icy Galilean satellites; they are the crystallization of amorphous ice by heating and degradation or amorphization of crystalline ice under the influence of intense fluxes of solar-wind particles and other particles (mainly O^+, S^+, and H^+) from the magnetosphere and radiation belts of Jupiter extending to 50–100 Jovian radii. It is worth stressing that the particle-radiation flux substantially changes with the distance from Jupiter: it decreases by approximately 300 times between Europa and Callisto (Dalton et al., 2010). At the same time, though the change of the temperature maximum from 132 K on Europa (Spencer et al., 1999) to 158 K on Callisto (Moor et al., 2004) is small, this leads to a difference in the rate of thermal crystallization of ice up to five orders of magnitude between the satellites (Dalton et al., 2010). Since the surface temperature of Europa is lower (due to the higher albedo), no crystallization of amorphous ice produced under the influence of intense radiation flux occurs there. Because of this, the ice surface layer (at least to a depth of about 1 mm) can be amorphous on Europa (Dalton et al., 2010). And, on the contrary, the more moderate radiation and higher temperatures favor the transformation of ice to a crystalline state on the surface of Callisto. Whereas on the surface of Ganymede, both ice forms are quite abundant (Dalton et al., 2010).

It follows from the IR characteristics that the non-icy materials of other types are present on the surface of Europa: sulfates of sodium and magnesium (like $MgSO_4$ and Na_2SO_4) and their hydrates. Such compounds could appear in an aqueous medium, as well as during the implantation of S^+, Na^+, and K^+ ions transported by the magnetosphere of Jupiter to Europa from the vicinity of the neighboring Io (McCord et al., 1997a; 1997b; 1998; 2010; Carr et al., 1998; Carlson et al., 1999; 2005; Orlando et al., 2005; Greenberg, 2010). Moreover, on these bodies, unusual molecules appearing under the constant exposure of ices (mostly H_2O and CO_2) to the solar ultraviolet radiation and high-energy fluxes of electrons and ions (see, e.g., McCord et al., 1998; Delitsky and Lane, 1998) were detected. On these bodies, SO_2 (Lane et al., 1981), CO_2, H_2S, H_2O_2 (Smythe et al., 1998; Carlson et al., 1999), and hydrates of sulfuric acid ($H_2SO_4 \cdot 8H_2O$, $H_2SO_4 \cdot 6.5H_2O$, and $H_2SO_4 \cdot 4H_2O$) (Carlson et al., 2005; McCord et al., 2010) were found. The experimental studies showed that the influence of fluxes of protons, electrons, and other charged particles on SO_2 and H_2S frozen into water ice under the surface temperature of Europa (86–130 K) leads to radiolysis and appearance of anions (SO_4^{2-}, HSO_3^-, and HSO_4^-) and cations (H_3O^+ and H_5O^+) that have specific absorption bands in the IR range (Moore et al., 2007). On the surfaces of icy Galilean satellites, the product of radiolysis is also molecular oxygen O_2 (sometimes O_3) that

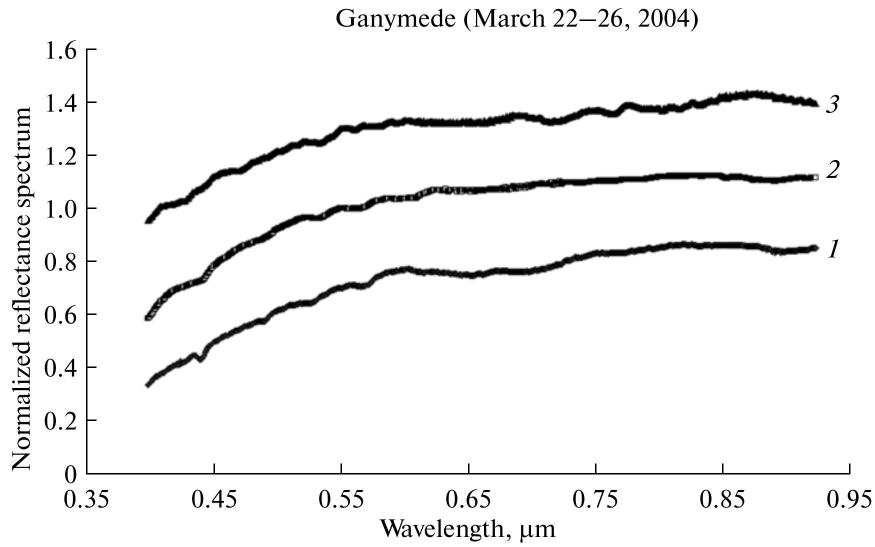

Fig. 2. The reflectance spectra of the Jovian satellite Ganymede (*1–3*) obtained on March 22–26, 2004. They are smoothed, normalized (to the value at $\lambda = 0.5503$ μm), and vertically shifted. The recording time and the errors of the reflectance spectra are listed in Table 1. Spectra *1* and *2* correspond to the trailing side of the satellite, and spectrum *3*, to the leading one.

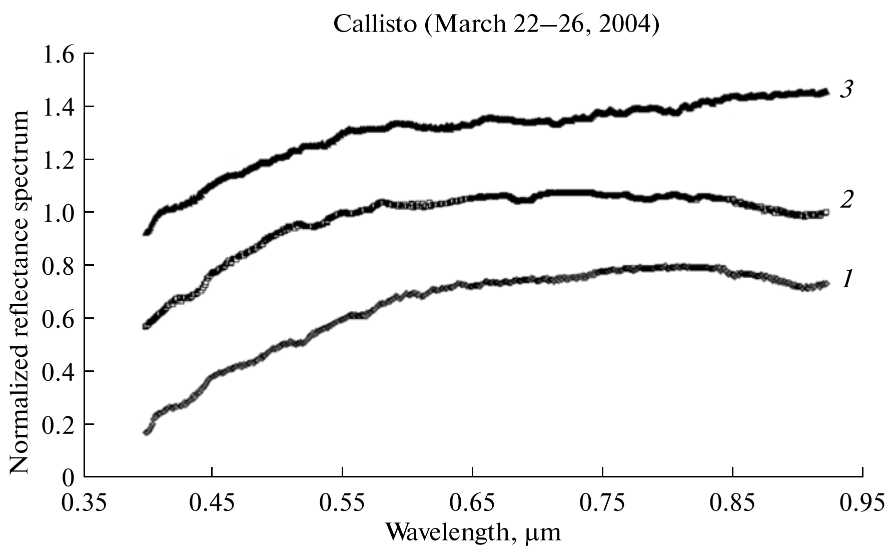

Fig. 3. The reflectance spectra of the Jovian satellite Callisto (*1–3*) obtained on March 22–26, 2004. They are smoothed, normalized (to the value at $\lambda = 0.5503$ μm), and vertically shifted. The recording time and the errors of the reflectance spectra are listed in Table 1. All three spectra correspond to the leading side of Callisto.

can be adsorbed into the water ice (Noll et al., 1995; Spencer and Calvin, 2002; Cooper et al., 2003).

As has been already mentioned, Europa, Ganymede, and Callisto orbit rather close to Jupiter (at the distances ranging within 9–26 Jovian radii) and, therefore, are subjected to somewhat varying tidal deformations warming up their interiors (e.g., Peale and Lee, 2002; Greenberg, 2010). Due to this, the conditions for global water oceans are maintained on these satellites. The models of the internal structure of the icy Galilean satellites of Jupiter, including their oceans, have been under development for a long time (e.g., Lewis, 1971; Consolmagno and Lewis, 1976; Kuskov and Kronrod, 2001; 2005; Kuskov et al., 2009). For example, there are several signs on Callisto that point to its incomplete differentiation; therefore, the presence of an internal ocean is considered problematic there (Schubert et al., 1981). However, as follows from the data acquired by the *Galileo* spacecraft, which found disturbances of the Jovian magnetic field near Europa and Callisto, indirect signs of the occurrence of the internal water layer do exist on Callisto

Table 1. The observational conditions and parameters of the Galilean satellites of Jupiter and the solar analog star

Spectrum no.	Date	UT (h m s)	α (h m s)	δ (° ′ ″)	Δ (AU)	r (AU)	φ (°)	V (m)	ω; L (°)	$M(z)$	σ_1	σ_2	σ_3
Europa (JII) ($T_{rot} = 3.5512^d$)													
1	2004 03 22	21 59 35	10 54 10	+08 32 52	4.474	5.416	3.8	5.7	0.000; 172.3	1.315	0.026	0.015	0.017
HD 101177	2004 03 22	23 40 51	11 38 45	+45 06 30	–	–	–	6.4	–	1.263	–	–	–
2	2004 03 23	20 58 39	10 53 31	+08 36 54	4.484	5.420	4.0	5.7	0.270; 269.5	1.245	0.023	0.014	0.015
HD 101177	2004 03 23	22 56 18	11 38 45	+45 06 30	–	–	–	6.4	–	1.161	–	–	–
3	2004 03 25	20 52 02	10 53 05	+08 39 10	4.495	5.420	4.3	5.7	0.832; 111.9	1.245	0.010	0.005	–
HD 101177	2004 03 26	02 23 45	11 38 45	+45 06 30	–	–	–	6.4	–	1.352	–	–	–
Ganymede (JIII) ($T_{rot} = 7.1546^d$)													
Spectrum no.	Date	UT (h m s)	α (h m s)	δ (° ′ ″)	Δ (AU)	r (AU)	φ (°)	V (m)	ω; L (°)	$M(z)$	σ_1	σ_2	σ_3
1	2004 03 22	22 38 08	10 53 47	+08 35 23	4.479	5.420	3.8	5.0	0.000; 271.8	1.409	0.018	0.010	0.017
HD 101177	2004 03 22	23 40 51	11 38 45	+45 06 30	–	–	–	6.4	–	1.263	–	–	–
2	2004 03 23	21 22 11	10 53 29	+08 36 59	4.489	5.426	4.0	5.0	0.132; 319.5	1.264	0.022	0.016	0.010
HD 101177	2004 03 23	22 56 18	11 38 45	+45 06 30	–	–	–	6.4	–	1.161	–	–	–
3	2004 03 25	21 08 33	10 53 10	+08 38 30	4.500	5.425	4.3	5.0	0.411; 59.8	1.259	0.010	0.009	–
HD 101177	2004 03 26	02 23 45	11 38 45	+45 06 30	–	–	–	6.4	–	1.352	–	–	–
Callisto (JIV) ($T_{rot} = 16.6890^d$)													
Spectrum no.	Date	UT (h m s)	α (h m s)	δ (° ′ ″)	Δ (AU)	r (AU)	φ (°)	V (m)	ω; L (°)	$M(z)$	σ_1	σ_2	σ_3
1	2004 03 22	23 06 15	10 54 40	+08 29 19	4.483	5.426	3.8	6.2	0.000; 68.7	1.511	0.017	0.009	0.016
HD 101177	2004 03 22	23 40 51	11 38 45	+45 06 30	–	–	–	6.4	–	1.263	–	–	–
2	2004 03 23	22 13 11	10 54 18	+08 31 37	4.484	5.422	3.9	6.2	0.058; 89.6	1.351	0.015	0.008	0.011
HD 101177	2004 03 23	22 56 18	11 38 45	+45 06 30	–	–	–	6.4	–	1.161	–	–	–
3	2004 03 25	21 33 04	10 53 19	+08 37 46	4.488	5.413	4.3	6.2	0.176; 132.4	1.289	0.011	0.009	–
HD 101177	2004 03 26	02 23 45	11 38 45	+45 06 30	–	–	–	6.4	–	1.352	–	–	–

The following notations are used: UT is the universal time; α is the right ascension; δ is the declination; Δ is the geocentric distance; r is the heliocentric distance; φ is the solar phase angle; V is the visible magnitude; ω is the relative phase of rotation (the relative rotational phase of the satellite at the moment of acquiring the first spectrum is assumed to be zero); L is the longitude of the subterrestrial point on the satellite; $M(z)$ is the air mass. The errors in the reflectance spectra of asteroids σ_1, σ_2, and σ_3 are the standard deviations at 0.44–0.45, 0.59–0.60, and 0.84–0.85 μm, respectively. After the satellite names, there are the sequence numbers of the reflectance spectra, which were obtained during three nights and are shown in the figures with the corresponding dates, and the number of the star in the HD catalog used as the solar analogue. The rotation/orbital periods of the Galilean satellites of Jupiter were taken from the website (http://nssdc.gsfc.nasa.gov/planetary/factsheet/joviansatfact.html); the longitude L of the subterrestrial point were calculated with the on-line code "HORIZONS" (http://ssd.jpl.nasa.gov/horizons.cgi#top).

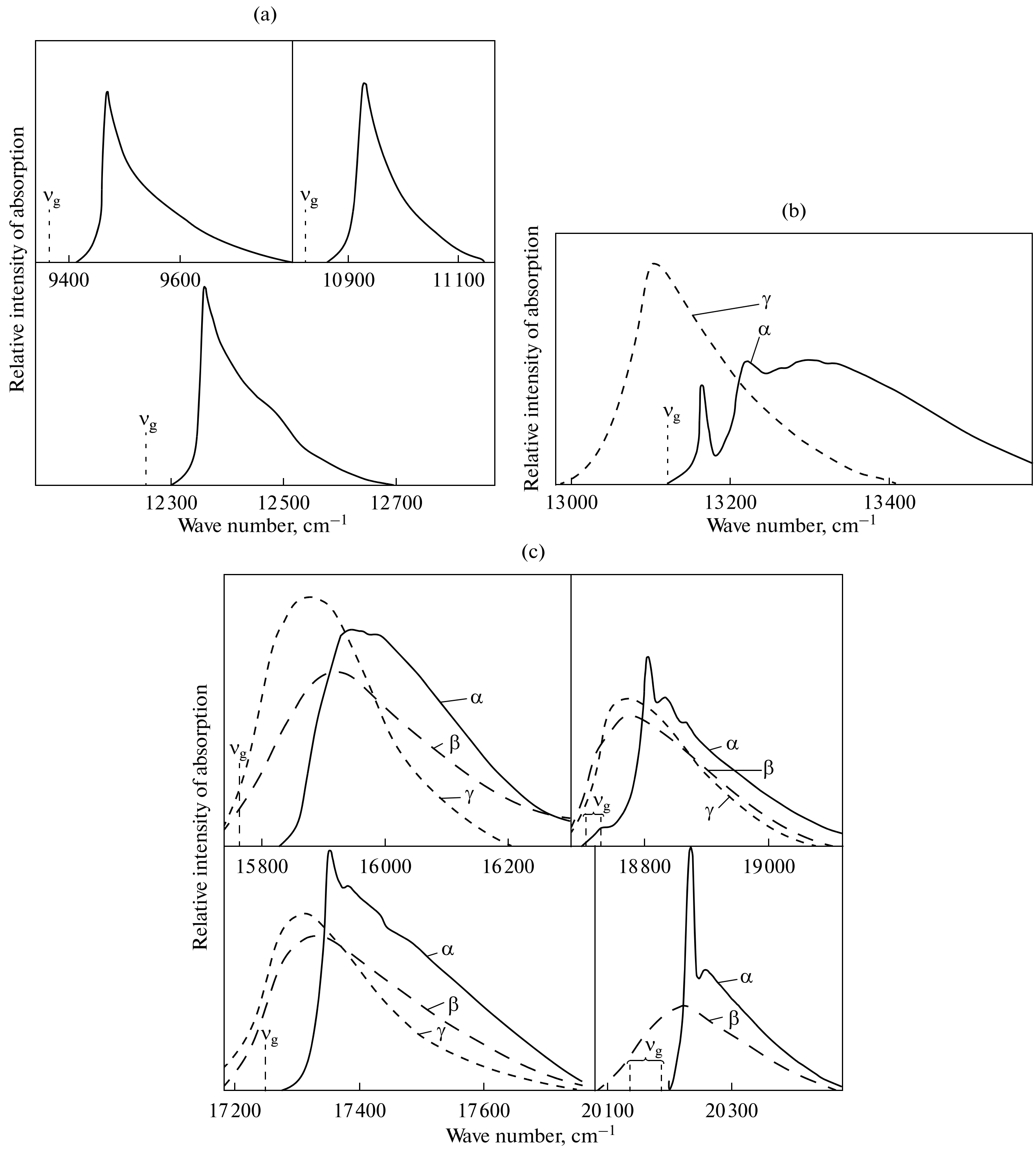

Fig. 4. The experimentally measured absorption spectra of solid molecular oxygen adapted from the paper by Landau et al. (1962). Indices α, β, and γ indicate the spectra corresponding to three modifications of solid O_2 described in the text. The wavelength values (in nanometers) corresponding to the maxima in the absorption spectra of the α modification of solid O_2 are listed in the text (the underlined values).

(Khurana et al., 1998; Stevenson, 2003). At the same time, there are practically no doubts about the presence of an internal water ocean on Europa. The depth of the water–ice envelope of Europa is estimated from 100 to 150 km depending on the distribution and composition of the initial material (e.g., Kuskov et al., 2009). It has been repeatedly proposed that the extraterrestrial life could arise and currently exists in the

(d)

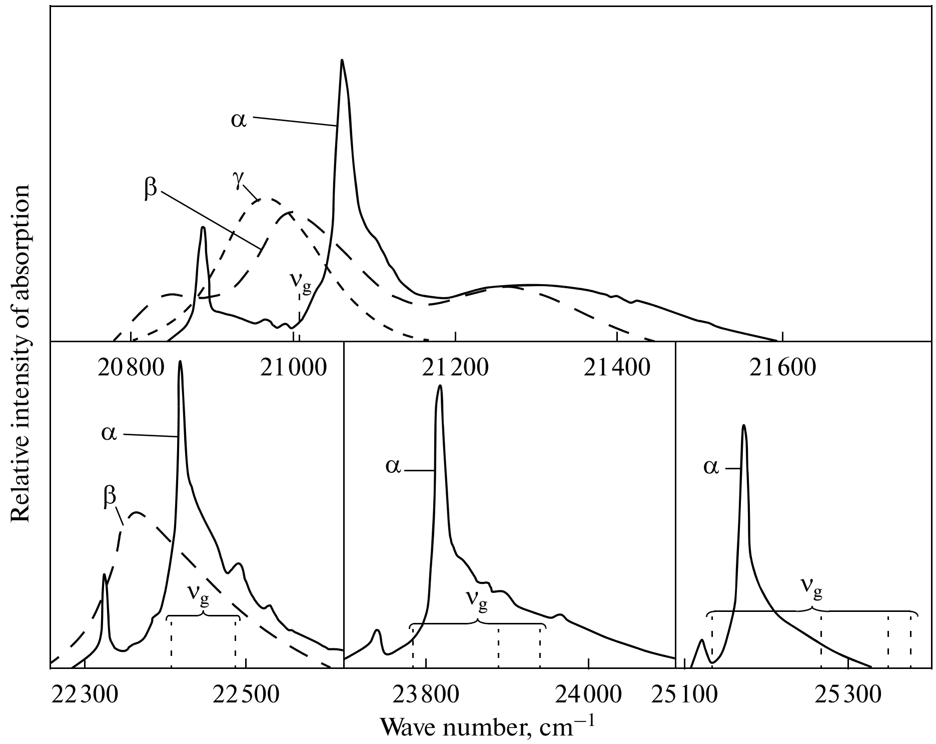

Fig. 4. (Contd.)

ocean on Europa (e.g., Reynolds et al., 1983; Marion et al., 2003; Prieto-Ballesteros et al., 2011). These suggestions stimulated the developing of the space mission for investigations of the surface of Europa (Zelenyi et al., 2010).

Due to a high scientific interest to the Galilean satellites of Jupiter and the prospects of a future space mission to them, it is important to acquire new observational, experimental, and model data rather than only to examine and summarize the information already available.

OBSERVATIONS OF EUROPA, GANYMEDE, AND CALLISTO AND INTERPRETATION OF THE CHARACTERISTICS OF THE REFLECTANCE SPECTRA OBTAINED

The spectra of the icy Galilean satellites of Jupiter were acquired in March 2004, with the use of the CCD spectrograph mounted on the 1.25-m telescope of the Crimean laboratory of the Sternberg Astronomical Institute. The spectrograph works in the range of 0.39–0.92 μm, and its spectral resolution is about ~8 Å (see Table 1). The spectrum of each of the objects was recorded in two sequential parts (0.39–0.71 and 0.65–0.92 μm) that were sewn together in processing. This procedure, as a rule, introduces no substantial errors, since the time interval between the recording of these parts of the spectrum is small (about 10 min) (Busarev, 1999; 2011b). The root-mean-square error of the calculated reflectance spectra was less than 1–2% in the center of the range 0.45–0.70 μm, and its values near the blue and red boundaries differed (depending on the observational conditions and the brightness of the objects), but they did not exceed 5–7%. The values of errors in each of the reflectance spectra are shown in Table 1. To exclude the noise component arising in the terrestrial atmosphere and due to the dividing of the initial spectrum by that of the solar analogue (when modeling the reflectance spectrum), the reflectance spectra were smoothed with the "running box average" method, and the spectrum continuum near the blue and red boundaries was extrapolated with polynomials. Over three nights (March 22–26, 2004), the same standard star—the solar analogue (HD 101177)—was observed to obtain the reflectance spectra and to determine the spectral transparency of the terrestrial atmosphere. The conditions for observations of the Galilean satellites of Jupiter and the star HD 101177 are presented in Table 1, and the normalized reflectance spectra of the satellites are displayed in Figs. 1–3. During the observations, the solar phase angle of the satellites varied within a small range, from 3.8° to 4.3°. We stress that the methods of the preliminary processing of the observational data and their smoothing and normalizing used here are exactly the same as those

Table 2. The weak absorption bands detected in the reflectance spectra of the icy Galilean satellites of Jupiter and their identification

Europa					
center position, λ_c, μm	width, Δλ, μm	relative intensity, %	element or compound	host material	sources
0.43	0.41–0.45	~4	O_2	Water ice	*
0.47	0.45–0.48	~1.5	O_2	Water ice	*
0.50	0.49–0.50	~1.5	Fe^{2+} or O_2?	Olivine or water ice?	* or **
0.52	0.51–0.53	~3	Fe^{2+}	Water-soluble salts or pyroxene?	*** or **
0.53	0.52–0.54	~3	O_2	Water ice	*
0.54	0.53–0.55	~3	O_2?	Water ice?	*
0.57	0.56–0.59	2–4	O_2	Water ice	*
0.62	0.61–0.62	~2	O_2	Water ice	*
0.77	0.76–0.77	~2	O_2	Water ice	*
0.86	0.70–0.92	~9	methane?	Water ice	
Ganymede					
center position, λ_c, μm	width, Δλ, μm	relative intensity, %	element or compound	host material	sources
0.43	0.41–0.45	3–4	O_2	Water ice	*
0.44	0.42–0.45	~3	O_2 and/or Fe^{3+}?	Water ice or hydrosilicates?	* and/or ****
0.44	0.43–0.45	~3	Fe^{3+}	Hydrosilicates	****
0.47	0.46–0.48	~2	O_2	Water ice	*
0.50	0.49–0.50	~1.5	Fe^{2+} or O_2?	Olivine or water ice?	** or *
0.53	0.52–0.55	2–3	O_2	Water ice	*
0.56	0.55–0.57	~1.5	O_2?	Water ice?	*
0.57	0.56–0.58	~2	O_2	Water ice	*
0.61	0.60–0.62	~2	O_2?	Water ice?	*
0.67	0.60–0.75	~8	Fe^{2+} and Fe^{3+}	Hydrosilicates	***
0.71	0.69–0.75	~7	Fe^{2+} and Fe^{3+}	Hydrosilicates	***
0.76	0.75–0.77	~5	O_2	Terrestrial atmosphere (A-band)	*****
0.90	0.88–0.92	~3	Fe^{2+}	Orthopyroxenes	** and ***
Callisto					
center position, λ_c, μm	width, Δλ, μm	relative intensity, %	element or compound	host material	sources
0.43	0.41–0.45	~3	O_2	Water ice	*
0.44	0.42–0.45	~3	O_2 and Fe^{3+}?	Water ice and hydrosilicates?	* and ****
0.47	0.46–0.49	~1.5	O_2	Water ice	*
0.48	0.47–0.49	~1.5	O_2	Water ice	*
0.52	0.51–0.53	~2	Fe^{2+}	Pyroxene	**
0.53	0.52–0.54	~2	O_2	Water ice	*
0.54	0.52–0.55	~2	O_2?	Water ice?	*
0.57	0.56–0.58	~2	O_2	Water ice	*
0.57	0.55–0.58	~2	O_2	Water ice	*
0.61	0.60–0.62	~2	O_2?	Water ice?	*
0.62	0.58–0.66	~2	Fe^{2+} and Fe^{3+}?	Hydrosilicates?	***
0.69	0.68–0.70	~3	O_2	Terrestrial atmosphere (B-band)	*****
0.71	0.59–0.85	~5	Fe^{2+} and Fe^{3+}	Hydrosilicates	***
0.90	0.85–0.95?	~10	Fe^{2+}	Orthopyroxenes	** and ***

Sources: * Landau et al. (1962), ** Platonov (1976), *** Burns (1993), **** Busarev et al. (2008), and ***** Kurucz (2005).
The table lists the bands that can be found in at least one of the obtained reflectance spectra of the object; the absorption bands at 0.43 and 0.57 μm are probably the combinations of narrower bands.

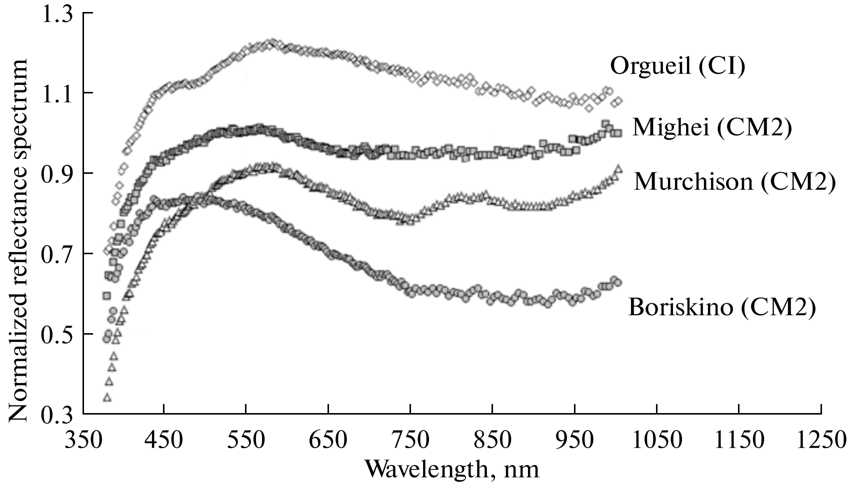

Fig. 5. The normalized (to the value at λ = 550 nm) and vertically shifted reflectance spectra of the crumbled samples of carbonaceous chondrites (the particle sizes are ≤0.25 mm) (Busarev and Taran, 2002). The sample names and their meteoritic groups are shown in the plot. The samples were taken for investigations from the collection of meteorites of the Vernadsky Institute of Geochemistry and Analytical Chemistry of the Russian Academy of Sciences.

applied to the processing of the spectrophotometric data on asteroids (Busarev, 1999; 2010; 2011a; 2011b).

Three reflectance spectra of Europa (T_{rot} = 3.5512^d; D = 3121.6 km) were acquired during the time interval close to its rotational period; and, therefore, they characterize almost the whole surface (Fig. 1 and Table 1). The recording time of three reflectance spectra of Ganymede (T_{rot} = 7.1546^d; D = 5262.4 km) approximately corresponds to a half period of its rotation (Fig. 2 and Table 1); and, therefore, they contain the data on its opposite sides. And, finally, three reflectance spectra of Callisto (T_{rot} = 16.6890^d; D = 4820.6 km) approximately cover a quarter of its surface (Fig. 3 and Table 1).

Identification and Interpretation of Weak Absorption Bands in the Visible Range

To identify weak absorption bands in the reflectance spectra of the icy Galilean satellites of Jupiter, the results of investigations of their most probable analogues were used. We have stressed above that water ice dominates on the surface of these bodies or is a rather abundant compound there. However, water ice produces no absorption bands in the visible range (e.g., Wagner et al., 1987). Because of this, the spectral characteristics of the most probable inclusions in water ice should be also considered. As has been noted, one of them on the surface of the satellites is molecular oxygen (Noll et al., 1995; 1996). It shows many characteristic absorption bands from the ultraviolet to IR range. The spectral positions of these bands remain approximately the same for the gaseous, liquid, and solid phase states of O_2; though their shape and intensity vary (Landau et al., 1962; Newnham and Ballard, 1998). In the compressed gas and condensed states of oxygen, the intensity of these absorption bands grows, which is explained by the formation of quasistationary complexes $(O_2)_2$, where simultaneous electron transitions may occur (e.g., Landau et al., 1962). Laboratory spectral investigations of solid molecular oxygen (Landau et al., 1962) showed that its three modifications α (stable at temperatures < 23.9 K), β (stable at 23.9 < T < 43.8 K), and γ (stable at 43.8 < T < 54.1 K (the melting temperature)) have several rather strong absorption bands in the visible range centered at <u>0.420</u>, 0.445, <u>0.446</u>, 0.479, 0.494, 0.532, 0.574, 0.575, <u>0.576</u>, <u>0.623</u>, <u>0.627</u>, <u>0.751</u>, <u>0.756</u>, 0.760, and 0.915 μm (the values corresponding to stronger bands are underlined). From the cited paper by Landau et al. (1962),

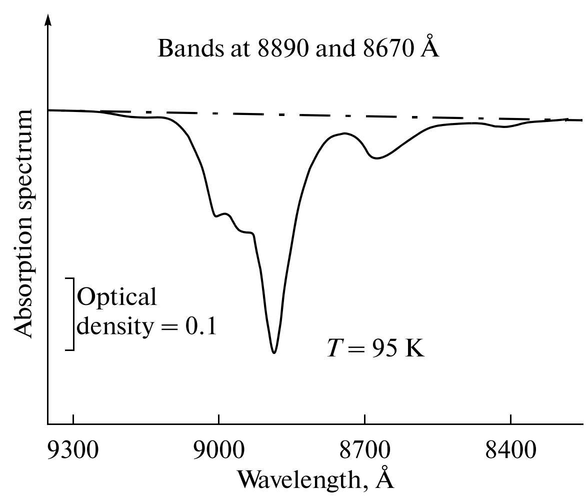

Fig. 6. The absorption spectrum of liquid methane (CH_4) in the range of 0.83–0.93 μm (in the plot, the wavelengths are expressed in angstrom units, and the scale direction is opposite to the usual direction). It was obtained at a temperature of 95 K. The plot is adapted from the paper by Ramaprasad et al. (1978).

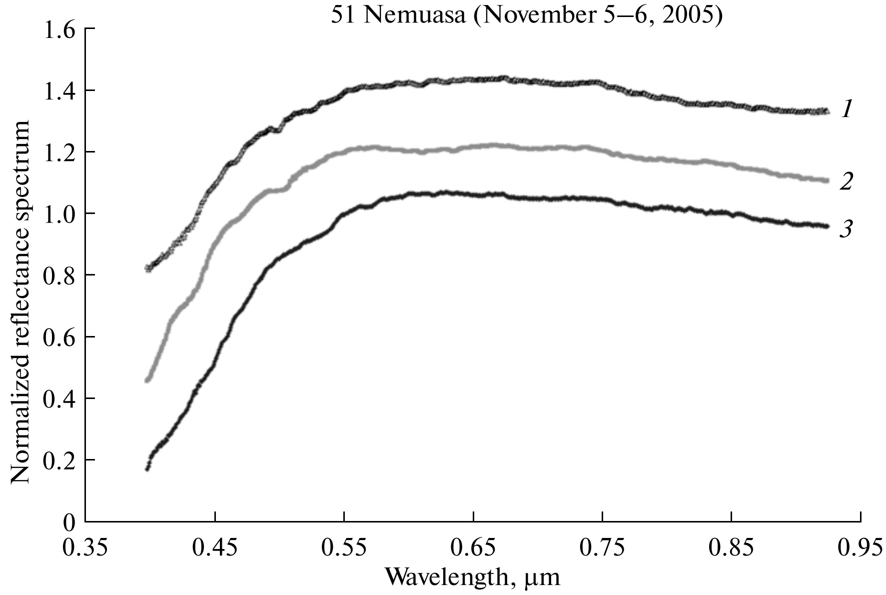

Fig. 7. The reflectance spectra of the C-type asteroid 51 Nemuasa (*1–3*) acquired on November 5–6, 2005. They are smoothed, normalized (to the value at $\lambda = 0.5503$ μm), and vertically shifted. The solar phase angle is 14.5°, and the rotation phases are close to each other (Busarev, 2011b).

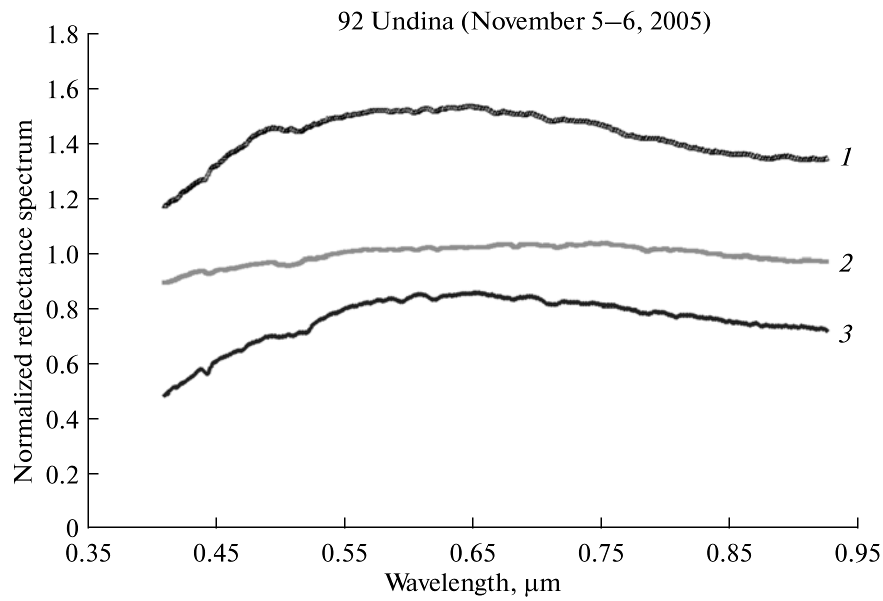

Fig. 8. The reflectance spectra of the X-class asteroid 92 Undina (*1–3*) acquired on November 5–6, 2005. They are smoothed, normalized (to the value at $\lambda = 0.5503$ μm), and vertically shifted. The solar phase angle is 5.2°, and the rotation phases are close to each other (Busarev, 2011b).

we took the absorption spectra (expressed in wave numbers, $1/\lambda$) for all three modifications of solid O_2 (see Figs. 4a–4d). The structural state of molecular oxygen adsorbed by the icy surface of the Galilean satellites is probably close to its state in solid forms, although it is at higher temperatures on Europa (140 K on average), Ganymede (156 K), and Callisto (168 K) (Richardson and Shum, 1968). In the reflectance spectra of the satellites under consideration, there are weak absorption bands (with a relative intensity of about 1–3%) (see Table 2), the wavelengths of which coincide with, or are close to, the values of the above-listed wavelengths of the α form of solid O_2 (see Figs. 1–3 and 4a–4d). It is important to note that such a coincidence was found in the reflectance spectra of the icy Galilean satellites in seven absorption bands at once (at 0.42, 0.45, 0.47, 0.49, 0.53, 0.576, and 0.756 μm). This result can be considered as a confirmation of the previous detection of molecular oxygen on these bodies that was made by two of the listed bands, at 5770 and 6275 Å (Spencer et al., 1995; 2002), as well as an identification of other absorption bands of O_2.

There are also other spectral features. For example, the large width of the absorption band at 0.41–0.45 μm and its position, which is somewhat shifted toward short wavelengths, attract attention in the reflectance spectra of all the icy Galilean satellites (Figs. 1–3). It was found earlier that the equivalent width of such an absorption band in the reflectance spectra of the crumbled samples of terrestrial low-iron serpentines, which are analogues of the material of primitive and hydrated asteroids, correlates well with the Fe^{3+} content (Busarev et al., 2008; Busarev, 2011b). From the presented list of the absorption bands of solid molecular oxygen (Landau et al., 1962), it follows that three absorption bands of adsorbed O_2 can be observed in the spectral range considered: at 0.420, 0.445, and 0.446 μm. These O_2 bands in the reflectance spectra of the icy Galilean satellites can overlap each other and mask the narrower absorption band of Fe^{3+}, if the latter exists. If we assume that iron can be present in different oxidized states in the hydrated silicate material, we may suggest that the non-icy material of the icy Galilean satellites contains Fe^{2+} and Fe^{3+}. We can verify this suggestion by the example of one of the spectra of Ganymede (Fig. 2, curve *1*), where a relatively narrow absorption band centered at 0.44 μm and induced, probably, by Fe^{3+} is clearly seen. It is similar to that observed in the reflectance spectra of asteroids (Busarev, 2011b). This spectrum may correspond to that portion of the surface of Ganymede, where there is less ice and more hydrosilicates containing iron. It is worth noting that, in the 0.60–0.75 μm range, the considered spectrum also contains a rather noticeable wide absorption band centered at 0.67 μm. Such a band can be induced by the process of electron intervalence transfer of the charge $Fe^{2+} \rightarrow Fe^{3+}$ in hydrated silicate compounds (Burns, 1993; Stewart et al., 2006). In the same spectrum, there is also a sign of an absorption band at 0.90 μm appearing, probably, due to the spin-allowed electronic transitions in Fe^{2+} in the crystal field of orthopyroxenes (Platonov, 1976; Burns, 1993). In the reflectance spectra of Callisto (Fig. 3, curves *1* and *2*), this absorption band is more intense. In some reflectance spectra of Europa (Fig. 1, curve *1*) and Callisto (Fig. 3, curve *1*), there is a weak absorption band at 0.52 μm induced, probably, also by the Fe^{2+} containing compounds. It resembles the absorption band in the reflectance spectra of terrestrial pyroxenes and asteroids of the high-temperature type (Platonov, 1976; Wagner et al., 1987; Gaffey et al., 1989; Busarev, 2011b).

We have previously obtained the reflectance spectra of the best known samples of carbonaceous chondrites (Busarev and Taran, 2002), whose matrix includes up to 90% of hydrosilicates (e.g., Dodd, 1981). It is seen from these spectra (see Fig. 5) that, depending on the structural characteristics of the material, carbonaceous chondrites show a wide absorption band in the range from ~550 to 1000 nm or a pair of bands with the centers close to those of the bands discovered on Ganymede and Callisto (at 0.67 and 0.90 μm). This can be considered as one more confirmation of the results obtained. Thus, we may conclude that there are a number of rather reliable spectral indications of the presence of heterovalent forms of iron (Fe^{2+} and Fe^{3+}) probably belonging to silicate compounds. However, in connection with a predominant (or considerable) portion of the ice component in the surface material of Europa, Ganymede, and Callisto, it would be interesting to answer the question of the origin of such iron-containing compounds. How could olivine, pyroxene, or their hydrated compounds containing Fe^{2+} and Fe^{3+} get to the surface of these satellites? It is evident that silicate compounds can be carried out from the upper mantle to the surface with magmatic and/or water fluxes due to the tidal heating of the interior of these bodies and the geologic activity connected with this, as well as due to the cracking of the ice crust. However, there is, probably, one more, "easier," way to do this. We consider this possibility in more detail in the next section.

In two spectra of Europa (Fig. 1, curves *1* and *2*), there is one more interesting feature, the absorption band at 0.86–0.90 μm. Its position cannot be explained by the above-described electronic mechanisms involving ions of oxygen and iron. The sulfuric compounds found on the surface of Europa do not manifest themselves in this range, since they have noticeable absorption bands only in the IR range (e.g., Carlson et al., 2005; Moore et al., 2007). It is important that the range of 0.80–0.90 μm is practically free of the telluric absorption bands (e.g., Kurucz, 2005), which apparently favors the observations. The absorption band at 0.86–0.90 μm was detected in the spectra of Europa during two photometric nights and, therefore, cannot be induced by any ignored instrumental or atmospheric effects (see Table 1). As follows from the experimental data (Ramaprasad et al., 1978; Grundy et al., 2002) (see Fig. 6), the absorption in this wavelength range can be caused by methane (CH_4). It is seen from Fig. 6 that this range contains a pair of overlapping bands of liquid methane with an absorption maximum at 0.89 μm. However, in the reflectance spectra of Europa, the absorption maximum is at 0.86–0.87 μm (Fig. 1, curves *1* and *2*). This can be an actual fact (the causes of which are still unknown) or the result of the distortion of the combined form of the considered absorption bands in the smoothing of the reflectance spectra near the spectral range boundary. It is evident that additional observations and new experimental investigations are required to specify more accurately the absorption profile at 0.86–0.89 μm in the reflectance spectrum of Europa.

It is worth noting that the determined temperature limits on the day side of Europa (120–140 K) (Spencer et al., 1999; Rathbun et al., 2012) are higher than the temperatures of the phase transition of methane. According to the handbook by Enokhovich (1962), methane freezes and boils at 90.5 and 111.5 K (at a pressure of 1 atm), respectively. Unfortunately, no experimental data are currently available on the temperatures of the phase transitions of methane in vacuum. There are only theoretical estimates (e.g., Zhang and Paige, 2009) showing that methane transits to the gaseous state at $T < 50$ K. Thus, it can be present on the surface of Europa in pure form only during a limited time and should quickly evaporate, since there is no atmosphere there. The other common form of methane exits in a wider temperature range. It is the clathrate hydrate or crystalline hydrate, where methane molecules are enclosed in the voids of a crystal lattice of water ice (e.g., Steed and Atwood, 2000). It is interesting that the spectral features (the position of absorption bands) of the crystalline hydrate of methane are generally identical to the characteristics of pure methane, and some of them become even more intense due to, probably, specific structural peculiarities of the crystalline hydrate (Dartois et al., 2010). Though the presence of clathrates (SO_2, CO_2, and H_2S) on the surface of the Galilean satellites was predicted long ago, only the compounds close to them have been detected so far (e.g., McCord et al., 1998; Carlson et al., 2005). For the present, methane clathrate has not been found either. This may be caused by its larger depth of stability in the surface material of the satellites relative to that of the other compounds (from a millimeter to several meters) (e.g., Prieto-Ballesteros et al., 2005). So, the question of whether methane is present on the surface of Europa in this or that form still remains open.

On the Possible Mechanism of Contamination of the Surface Material of Europa, Ganymede, and Callisto

The case in question is the delivery of the foreign material to the surfaces of celestial bodies lacking atmospheres during impact events. The significant scale of this process have been already confirmed in the investigations of many bodies of the Solar system. Atypical materials containing hydrosilicates and similar to carbonaceous chondrites have been found on asteroids of high-temperature types (Rivkin et al., 1995; Busarev, 2002; 2010; 2011a; 2011b). Water ice and bound aqueous compounds were discovered on the Moon (Pieters et al., 2009; Mitrofanov et al., 2010), and hydrosilicates and carbonaceous chondrite forms on Vesta (Hasegawa et al., 2003; Busarev et al., 2007a; Busarev, 2010; De Sanctis et al., 2012). The studies of the impact formations on the Earth and the modeling of impact processes show that a portion of the impactor material is not subjected to strong heating in the collision of two bodies and safely reaches the target's surface intact (e.g., Melosh, 1989). The portion of such undamaged material increases if the relative velocity of the colliding bodies decreases. Thus, the iron-containing silicate compounds, including the hydrated compounds, could be delivered to the surfaces of the icy Galilean satellites of Jupiter mainly during the falls of meteoroid and asteroid bodies. This inference is true for Ganymede and, even more, for Callisto, because the exposure ages of their surfaces are high. The substantial icy component of the material of these satellites of Jupiter makes such foreign material more noticeable in comparison to the bodies of mainly silicate composition, for example, asteroids. This means that the icy satellites of Jupiter, especially those of lower albedo, Ganymede and Callisto (Johnson and McCord, 1970; 1971), and the satellites of the other giant planets may resemble the asteroids of primitive or hydrated types. This is also confirmed by the results of our observations. A relatively narrow absorption band of Fe^{3+} at 0.44 μm, a rather wide absorption band in the range of 0.60–0.75 μm ($Fe^{2+} \rightarrow Fe^{3+}$), and a weak absorption band at 0.90 μm (Fe^{2+}) in the reflectance spectrum of Ganymede (Fig. 2, curve *1*), as well as the analogous band in the reflectance spectra of Callisto (Fig. 3, curves *1* and *2*), demonstrating the increasing intensity, are similar to the features in the reflectance spectra of asteroids. For comparison, we present here the characteristics of the C-class asteroid 51 Nemausa ($p_v = 0.093$) (Fig. 7), of carbonaceous-chondrite composition, and the hydrated asteroid 92 Undina ($p_v = 0.251$) (Fig. 8) (Busarev, 2011b) with a high-temperature base mineralogy. The surface of Undina can be covered with patches of hydrosilicates apparently delivered, as in the case of 4 Vesta, during the falls of the bodies of carbonaceous-chondrite composition (Busarev, 2010; 2011b; De Sanctis et al., 2012). The main taxonomic classifications characterize 51 Nemausa as an asteroid of a low-temperature type with carbonaceous-chondrite composition. Its spectral class is "CU" according to the classification by Tholen (1989), while its type is "Ch" (a sharp decrease of the reflectance in the UV range and a wide, but shallow, absorption band at 0.7 μm) according to Bus and Binzel (2002) and "Cgh" (the positive slope of the continuum in a long-wavelength range starts from 1.1 μm) according to Bus–DeMeo (DeMeo et al., 2009). The spectral characteristics of 92 Undina correspond to the high-temperature mineralogy and, simultaneously, to the presence of hydrosilicates on the surface. Its class is "X" according to Tholen (1989), "Xc" (the reddish spectrum contains practically no absorption bands, and its shape is slightly curved in the middle and long-wavelength parts) according to Bus and Binzel (2002), and "Xk" (it is specified that the asteroid may have a weak absorption band between 0.85 and 1 μm) according to Bus–DeMeo (DeMeo et al., 2009). It is seen from

Figs. 2, 3, and 8 that a general shape of the reflectance spectrum of Undina resembles those of Ganymede and Callisto. A narrow absorption band at 0.44 μm (Fe^{3+}) in the spectrum of Undina (Fig. 8) is practically identical to that in the spectrum of Ganymede (Fig. 2, curve *1*).

CONCLUSIONS

The analysis of the reflectance spectra of Europa, Ganymede, and Callisto obtained in the spectral range of 0.39–0.92 μm shows that they contain numerous weak absorption bands of absorbed molecular oxygen. This is apparently connected with the radiative implantation of O^+ ions into the surface material of the satellites, where the ice component dominates or is substantial, which favors the formation and accumulation of molecular oxygen. Identification of these absorption bands in the reflectance spectra of Europa, Ganymede, and Callisto became possible due to, first, the high transparency of water ice and oxygen molecules saturating it (which results in the considerable increase of the relative intensity of the diffuse component having passed through the material in the reflected light flux). The second cause is the high intensity of the absorption bands of molecular oxygen itself, being close to the condensed state. Moreover, in the reflectance spectra of the Galilean satellites (especially, Ganymede and Callisto), there are absorption bands that can be interpreted as signs of the combination of two- and three-valent iron being present in the material of the satellites. As the investigations of the terrestrial samples of hydrosilicates and carbonaceous chondrites (e.g., Fig. 5) show, the iron forms of different valence are typical of the hydrated silicate material subjected to the long-term influence of an aqueous medium. On Europa, the iron-containing compounds (if they are water-soluble) could be potentially carried up from the ocean bottom to the surface by water flows. On Ganymede and Callisto, hydrosilicates (like montmorillonite, serpentines, etc.) could be a component of the surface material due to the supposed incomplete differentiation of these bodies. At the same time, it seems more probable that the Fe^{2+} and Fe^{3+} containing silicates were also delivered to the surfaces of all icy Galilean satellites of Jupiter during the falls of meteoroid and asteroid bodies. The consequences of this process can be most significant on Ganymede and Callisto, due to the great age of their surface material.

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