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SPECTRAL GEOMETRIC ALBEDO OF THE GALILEAN SATELLITES, 0.3 TO 2.5 MICRONS*

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ABSTRACT

The spectral geometric albedos for the Galilean satellites of Jupiter were determined over the spectral range 0.9–2.5 μ with a spectral resolution of 0.05 μ. These observations were combined with albedos for the 0.3–1.1-μ spectral region taken from earlier work. The spectral albedo curves confirm the decrease in albedo beyond 1.0 μ for J II and J III. Jupiter I and J IV have relatively constant albedos from 1.0 to 2.5 μ. The curve for J III appears to show a relative minimum near 1.6 μ, as suggested by other observers. No spectral absorption feature is identifiable in the curve of J III near 2.0 μ.

The infrared spectral albedos for J II and J III are similar to the spectra of frosts and not to those of common silicates. Considering only the infrared reflection spectrum, the most likely possibilities for surface composition are water frost or hydrated ammonia frost. The lack of features in the infrared spectra of J I and J IV does not preclude the possibility of frosts on their surfaces. The visible reflectivities of the satellites (0.3–1.0 μ) do not resemble the reflectivities of pure frosts or of common silicates. Contaminent chromophors such as polysulfide compounds or ice radiation damage may produce this coloring at visible wavelengths.

I. INTRODUCTION

Measurements of the spectral reflectivities of the four Galilean satellites of Jupiter were made during June 1970 with the 200-inch telescope of the Hale Observatories. The infrared reflectivities of these bodies are particularly important, since their visible spectra (0.3–1.1 μ) allow no positive identification of surface compositions (Johnson 1971; Johnson and McCord 1970). Previous infrared measurements at lower spectral resolution (Moroz 1965; Kuiper 1961) have indicated that J II and J III have lower reflectivities in the infrared than in the visible, similar to some ices, while J I and J IV have relatively constant reflectivities from 0.8 to 2.5 μ. Measurements from 1 to 1.7 μ of J III at higher resolution indicate a depression in the reflectivity of J III in the region of 1.6 μ (Gromova, Moroz, and Cruikshank 1970). Recent observations in the region greater than 3 μ indicate that all the satellites but J I absorb solar radiation strongly in the 3–5-μ region (Gillett, Merrill, and Stein 1970).

II. OBSERVATIONS

The measurements were made by using a lead sulfide cell cooled by liquid nitrogen. The spectral range 0.9–2.5 μ was covered by using an interference filter ($\Delta\lambda \sim 0.05$) (cf. McCord and Westphal 1971). The sky signal was subtracted by using a double-beam photometer with the beams chopped at 10 Hz. A Brower lock-in amplifier, tuned to 10 Hz, and a strip-chart recorder were used to amplify and record the signal. The two beams were balanced by measuring the sky in both beams several times during an observation. Table 1 gives information on the observations. Arcturus (α Boo) was calibrated as a standard source by using flux values derived from Hyland and Neugebauer (1970) in the regions 1.55–1.80 μ and 2.00–2.40 μ. In the remaining spectral regions, flux values for α Boo were determined by first measuring the ratio of the spectral fluxes from α Boo and α Lyr and then applying values for the flux from α Lyr obtained from the model of

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TABLE 1

DATE OF EACH OBSERVATION AND THE ORBITAL AND SOLAR PHASE ANGLES OF EACH SATELLITE AND THE TIME OF OBSERVATION

Object	Date (1970 UT)	Orbital Phase	Solar Phase	Object	Date (1970 UT)	Orbital Phase	Solar Phase
J I........	June 17	60°	9.24	J II, J III..	June 23	47°	9.77
	June 19	115°	9.43		June 21	141°	9.60
	June 25	246°	9.91		June 21	141°	...
	June 26	90°	9.98		June 27	83°	10.05
					June 28	134°	10.11

Schild, Peterson, and Oke (1971). The flux ratio satellite/α Boo, when multiplied by the α Boo flux and divided by solar flux values obtained from Labs and Neckel (1968) (as modified to allow for the effects of solar lines on the filter bandpasses) gave satellite reflectivities. The fluxes used in reducing the satellite observations are tabulated in Table 2.

In order to calculate geometric albedo from the reflectivity it is necessary to assume a diameter and a dependence of brightness on solar phase angle. The phase coefficients given by Johnson (1971) were used to reduce the measurements to opposition. The mean diameters given by Sharonov (1958),

$$\text{J I} = 0''.93,\ \text{J II} = 0''.83,\ \text{J III} = 1''.29,\ \text{J IV} = 1''.26 \text{ at 5 a.u.},$$

and used by Johnson (1971), were adopted here, also. It should be noted that values of the diameters are still quite uncertain and represent the major uncertainty in the calculation of the geometric albedos.

III. RESULTS

The geometric albedos calculated are shown in Figure 1 and listed in Table 3. No separation of the infrared data by orbital phase was made because of the small number of runs available; however, most of the data for each satellite refer to the same side (see Table 1). Data from 0.3 to 1.1 μ were taken from Johnson (1971) for the side of the satellite to which the majority of the infrared data refer. It should be noted that the 0.3–1.1-μ data have not been adjusted to match the infrared data and the close match in the region of overlap with the infrared data (0.8–1.1 μ) indicates the level of internal consistency in our calibration of α Boo with respect to α Lyr (which was the prime standard for the visible work). Also shown are data from Moroz (1965) and *UBVRI* points from Harris (1961). The latter data were scaled to match our measurements near 0.8 μ, since they refer to different diameters and orbital phases.

The geometric albedo of J I remains at a value near unity from 1 to 2.5 μ; no absorption features can be identified. Jupiter II and J III both show a significant drop in albedo beyond 1 μ, as indicated by the earlier low-resolution points. In addition, the present work suggests a minimum in the region of 1.6 μ for J III which was also indicated by Gromova, Moroz, and Cruikshank (1970). Unfortunately, the strong telluric water absorptions in the 1.4- and 1.9-μ region make the identification of this absorption minimum difficult. The albedo of J III from 2.0 to 2.4 μ shows no clear features but remains at about the same average level as in the 1.4–1.8-μ region. The albedo of J II shows similar behavior to that of J III from 1.0 to 1.8 μ. Possible absorption minima are obscured by the scatter in the data. No data were obtained beyond 1.8 μ for J II.

TABLE 2

SPECTRAL FLUX VALUES FOR α LYRAE, α BOOTES, AND THE SUN USED IN THE REDUCTION OF THE SATELLITE OBSERVATIONS

$\lambda(\mu)$	α Lyr ($\times 10^{-9}$ W m^{-2} μ^{-1})	α Boo ($\times 10^{-8}$ W m^{-2} μ^{-1})	Sun (W m^{-2} μ^{-1})	$\lambda(\mu)$	α Lyr ($\times 10^{-9}$ W m^{-2} μ^{-1})	α Boo ($\times 10^{-8}$ W m^{-2} μ^{-1})	Sun (W m^{-2} μ^{-1})
0.906....	7.89	3.67	894	1.705....	0.97	1.51	205
0.948....	7.15	3.57	818	1.750....	0.87	1.37	186
1.002....	6.06	3.48	735	1.792....	0.82	1.23	172
1.053....	5.34	3.15	655	1.847....	0.74	1.14	154
1.101....	4.35	2.88	600	1.907....	0.66	1.02	138
1.150....	3.95	3.00	540	1.959....	0.57	0.90	126
1.199....	3.40	2.66	504	1.997....	0.56	0.88	117
1.253....	2.88	2.46	445	2.052....	0.50	0.80	106
1.308....	2.46	2.31	405	2.096....	0.47	0.74	98
1.349....	2.24	2.46	375	2.156....	0.40	0.68	89
1.402....	1.96	2.52	342	2.195....	0.39	0.64	83
1.454....	1.71	2.27	317	2.248....	0.36	0.59	79
1.504....	1.52	2.08	294	2.300....	0.34	0.51	70
1.556....	1.34	1.88	270	2.359....	0.31	0.43	64
1.604....	1.24	1.73	249	2.394....	0.29	0.41	61
1.658....	1.07	1.62	225	2.452....	0.26	0.37	56

NOTE.—The α Lyr flux is from model calculations of Schild *et al.* (1971). The α Boo flux is from our observations relative to α Lyr and from Hyland and Neugebauer (1970). The solar flux is from Labs and Neckel (1968), modified to conform to the bandpasses of our filters.

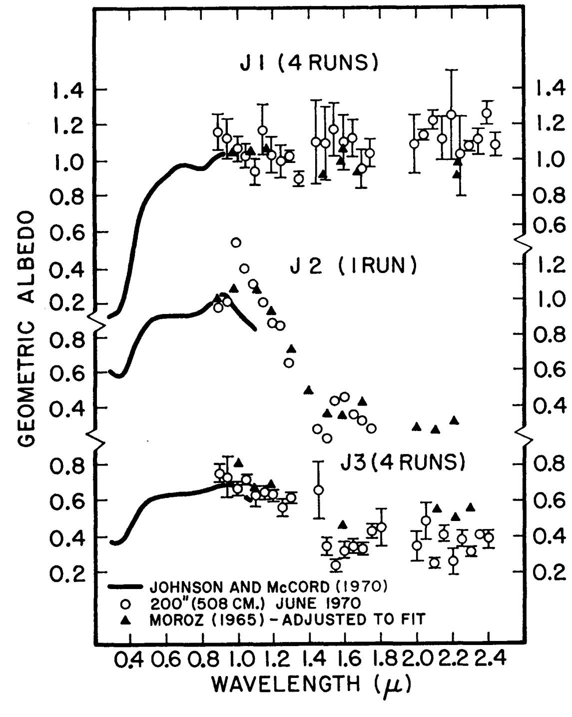

FIG. 1.—Geometric albedos of J I, J II, and J III from 0.3 to 2.4 μ. Mean radii for the satellites were taken from Sharonov (1958).

TABLE 3

GEOMETRIC ALBEDOS OF THE SATELLITES AND THE FORMAL STANDARD DEVIATIONS OF THE MEAN

A.

$\lambda(\mu)$	J I	σ	J II	σ	J III	σ
0.301.......	0.110	0.032	0.643	0.014	0.396	0.007
0.319.......	0.172	0.004	0.698	0.012	0.396	0.024
0.338.......	0.166	0.001	0.566	0.003	0.355	0.002
0.358.......	0.156	0.001	0.555	0.008	0.362	0.003
0.383.......	0.330	0.006	...	0.006	0.594	0.017
0.402.......	0.369	0.001	0.670	0.003	0.474	0.005
0.433.......	0.552	0.006	0.746	0.005	0.539	0.006
0.467.......	0.688	0.012	0.804	0.006	0.568	0.006
0.498.......	0.811	0.001	0.864	0.003	0.587	0.004
0.532.......	0.838	0.020	0.909	0.004	0.613	0.005
0.564.......	0.851	0.003	0.899	0.002	0.615	0.003
0.598.......	0.899	0.013	0.905	0.001	0.625	0.003
0.633.......	0.931	0.010	0.908	0.003	0.632	0.004
0.665.......	0.958	0.006	0.899	0.003	0.630	0.003
0.699.......	0.959	0.003	0.899	0.003	0.627	0.005
0.730.......	0.973	0.010	0.902	0.004	0.632	0.004
0.765.......	0.968	0.011	0.923	0.005	0.637	0.007
0.809.......	0.950	0.006	0.918	0.004	0.647	0.006
0.855.......	0.992	0.001	1.020	0.007	0.674	0.006
0.906.......	1.019	0.001	1.033	0.008	0.682	0.004
0.948.......	1.042	0.008	0.996	0.012	0.700	0.011
1.002.......	1.048	0.024	0.913	0.05	0.659	0.028
1.053.......	1.048	0.024	0.882	0.02	0.602	0.053
1.101.......	1.021	0.070	0.822	0.05	0.595	0.091

B.

$\lambda(\mu)$	J I	σ	J II	J III	σ
0.906..........	1.17	0.10	0.96	0.75	0.05
0.948..........	1.13	0.11	0.99	0.73	0.11
1.002..........	1.06	0.06	1.33	0.66	0.02
1.053..........	1.02	0.07	1.19	0.72	0.02
1.101..........	0.94	0.07	1.09	0.63	0.05
1.150..........	1.17	0.14	0.99	0.64	0.04
1.199..........	1.03	0.10	0.87	0.64	0.03
1.253..........	0.99	0.09	0.85	0.57	0.05
1.308..........	1.02	0.03	0.65	0.61	0.02
1.349..........	0.90	0.04	...	...	...
1.454..........	1.10	0.23	0.27	0.65	0.17
1.504..........	1.09	0.20	0.22	0.34	0.05
1.556..........	1.17	0.15	0.44	0.23	0.02
1.604..........	1.10	0.15	0.45	0.32	0.04
1.658..........	1.12	0.11	0.35	0.34	0.03
1.705..........	0.95	0.11	0.33	0.33	0.05
1.750..........	1.03	0.08	0.28	0.40	0.05
1.792..........	...	...	...	0.45	0.11
1.959..........	...	...	...	0.72	0.04
1.997..........	1.09	0.17	...	0.34	0.09
2.052..........	1.14	0.01	...	0.48	0.10
2.096..........	1.23	0.10	...	0.24	0.03
2.156..........	1.11	0.12	...	0.41	0.04
2.195..........	1.25	0.25	...	0.26	0.07
2.248..........	1.02	0.22	...	0.38	0.04
2.300..........	1.07	0.03	...	0.31	0.02
2.359..........	1.11	0.08	...	0.41	...
2.394..........	1.25	0.07	...	0.39	0.05
2.452..........	1.09	0.07	...	0.73	...

NOTE.—The visible data are from Johnson (1971) modified to conform to improvement in stellar and solar flux values.

Measurements of J IV were made under poor observing conditions. However, data that were obtained indicate that no major features are present in the 1–2-μ spectral reflectivity. This is in agreement with Moroz (1965).

IV. DISCUSSION

Spectral features in the region 1–2.5 μ such as those evident in the reflectivities of J II and J III are commonly associated with frosts. The decrease in the reflectivities of J II and J III beyond 1.0 μ is unlike the behavior of most silicate reflectivities. Silicates generally have flat or gradually increasing reflectivities in the 1.0–2.0-μ region, with only shallow absorptions and geometric albedos of 0.25–0.50 (Adams and Filice 1967; Hunt and Salisbury 1970). Moroz (1965) suggested that the depressions in his spectra of J II and J III were due to ice on the surface of these satellites. Gromova, Moroz, and Cruikshank (1970) suggest that a minimum in the reflectivity of J III near 1.6 μ may be due to either ammonia or water frost. However, in a solar-abundance model of the satellite compositions, water will be much more abundant than ammonia, and ammonia hydrates will be stable relative to pure ammonia frosts (Lewis 1971). Laboratory studies of such hydrated frost have not yet been made.

The apparent lack of absorptions in the reflectivities of J I and J IV does not necessarily mean that frosts are absent on their surfaces. Variations in particle size created by different conditions of freezing may make such absorptions too weak to detect (Kieffer 1970). Indeed, the high albedo of J I and the low density of J IV suggest that frost may be present on both. The presence of some frost on the surface of J IV is also indicated by the absorption between 3 and 5 μ reported by Gillett, Merrill, and Stein (1970).

The visible (0.3–1.1 μ) reflectivities of the satellites are not similar to the reflectivity of pure frosts (Johnson and McCord 1970). The reflectivities are qualitatively similar to that of Saturn's ring B (Lebofsky, Johnson, and McCord 1970). As with Saturn's rings, it appears to be difficult to produce the pronounced decrease in reflectivity in the blue and ultraviolet which these satellites exhibit by simple mixing of ices and dark silicates. Possible solutions to this problem may lie in complex chromophors such as polysulfides proposed by Lewis and Prinn (1970) for the coloring agents in Jupiter's bands or in ices damaged by solar ultraviolet radiation.

The spectral reflectivities of the Galilean satellites reported here do not allow a definite identification of the surface material, but some type of water or ammonia hydrate frost is the best possibility for J II and J III; silicates seem unlikely. More laboratory data on frost systems with hydrated ammonia, radiation damage, and various possible chromophors such as polysulfide are needed. Also, more precise infrared reflection spectra of higher spectral resolution for all four satellites are required.

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