NO. 187 COMMENTS ON THE GALILEAN SATELLITES

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ABSTRACT

The surface deposits of the Galilean satellites, especially Io, are examined in the light of some early and some very recent observations. Io, with probably a thin sulfur deposit in the lower latitudes and orange polar caps presumably composed of sulfur compounds, stands apart from the other three satellites.

1. Early Color and Spectral Observations

The unusually orange color of JI, Io, was discovered by Hertzsprung in 1911. It has been a challenge to determine its physical meaning. The author, in collaboration with the late Dr. D. L. Harris, made a number of observations of Io and the other three large satellites in the 1950's with the 82-inch telescope of the McDonald Observatory. The photometric, colorimetric, and eclipse data were published in Harris' excellent chapter in Volume III of THE SOLAR SYSTEM series (Kuiper and Middlehurst, 1961). Attention is called to the Io color curve between 0.35 and 0.80µ by Harris (*op. cit.* p. 304), showing the exceptional properties of Io, approximated only by the satellite Titan of Saturn, which, however, differed in the red and near-IR owing to its CH_4 absorptions.

The writer endeavored to extend our knowledge of the Jovian satellites beyond 1µ, both by photometry and by low-resolution spectroscopy. Both were carried out with the 82-inch telescope in 1956. My photometry was quoted by Harris in his Table 19 (*op. cit.* p. 305) which is repeated for ready reference in Table I. It was clear from this photometry that Io and Callisto had roughly constant albedos from 1-2µ, but that Europa and Ganymede were deficient at the longer wavelengths.

TABLE I

INFRARED OBSERVATIONS OF PLANETS AND SATELLITES

Planet or Satellite	I(2µ)/I(1µ)	Planet or Satellite	I(2µ)/I(1µ)
Sun	1.00	Mars	1.00
Venus	1.61	Io	1.06
Saturn	0.47	Europa	0.66:
Saturn's Ring	0.45	Ganymede	0.63
Jupiter	0.21	Callisto	0.95
Uranus	0.06:	Titan	0.20:
Mercury	3.5		

This was shown independently in my low-resolution spectra obtained between 0.8µ and 2.5µ. The resolution in these spectra was just sufficient to show the 1.6µ and 2.2µ transmission peaks, well offset by the strong H_2O absorptions at 1.4 and 1.9µ. The quantities so derivable were the intensity ratios 0.8/1.6/2.2µ. Figure 1 reproduces some traces of the four Jovian satellites so obtained as well as of the Ring of Saturn. Solar-type stars were used as comparisons, among them ηBoo, which showed spectra almost identical to those of JI. It followed that the 1.6 and 2.2µ maxima were deficient in intensity in both JII and JIII, but not in JI and JIV. The deficiencies were very marked in the Saturn Ring. The ratios 1.6/0.8µ were found as follows:

Sun	0.55	JIII	0.31
JI	0.53	JIV	0.54
JII	0.27	S.Ring	0.23

On the basis of these results I stated (1957): "The spectrometer tracings show striking differences between the four Galilean satellites of Jupiter. I and IV roughly resemble the solar and lunar curves between 1 and 2.5µ, but III and particularly II are markedly different, in the sense that the spectrum beyond 1.5 is reduced in intensity by a factor of 2-3. This is most readily explained by assuming that II and III are covered by H_2O snow. The albedo and color of II in visual light are compatible with this hypothesis, while III, which is darker, may be covered with snow contaminated with silicate dust. The rate of evaporation of snow, even if exposed to a vacuum, is shown not to be excessive at the distance of Jupiter. Good records of Saturn rings confirm the earlier result that they are composed of snow".

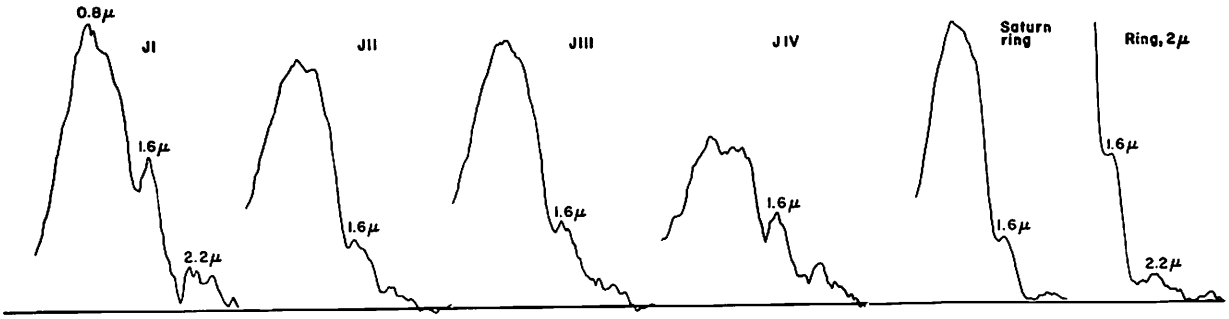

Figure 1 Spectrometer traces of Galilean satellites and Ring of Saturn, 82-inch telescope (1956)

The sensitivity of the PbS cells has not markedly increased during the past two decades and no substantially higher-resolution spectra could be acquired until the development of Fourier spectroscopy. A determined effort was made to obtain such spectra for the Jovian satellites with the 61-inch telescope in 1970, jointly with Drs. U. Fink and H. Larson. The following quotation is taken from my 1970 report to NASA covering work done under Research Grant NGL-03-002-002: "... preliminary results on the Jupiter satellites. The latter are rather faint for a 60-inch aperture, so that we had to reduce the spectral resolution. The interferometer sweeps are 2 secs. for full resolution but 1/2 sec. for the resolution on the satellites. We got 8-3/4 hrs. of integration time on Ganymede, over three nights; 5-1/4 hrs. on Io, 4 hrs. on Callisto, and 3 hrs. on Europa; thereupon the tens of thousands of interferograms were co-added and reduced. In spite of the considerable time spent in the reductions we have concluded that the results are still provisional and must be strengthened by further observation, scheduled to begin early 1971. To illustrate the records so far obtained, we are reproducing in Figs. (2) and (3) the spectra of all four satellites compared to the moon, plotted with two resolutions, 80 and 200 cm^{-1}. The ordinates were adjusted to the moon around 8000 cm^{-1} (7500-8800 cm^{-1}, or 1.14-1.33μ); no important absorptions are expected there. These satellite spectra are provisional, and we have omitted the parts below 3000 cm^{-1} ($\lambda > 3.33\mu$), where there is evidence of some uncompensated sky radiation in the results". (The numbers of the Figures in parentheses have been changed to correspond to the numbers used here).

Figures 2 and 3, due to the joint efforts by Drs. U. Fink, H. Larson, and the writer, are unaltered copies of the NASA 1970 report (dated February 4, 1971). These results were challenging but, as stated, still considered of insufficient quality for final publication; in particular, the reality of the features in the Callisto spectrum near 6300 and 4700 cm^{-1} was considered in question. The ice absorptions on Europa and Ganymede, announced in 1957, were plainly shown and clearly real. The recent spectra in *LPL Communication No. 186* have justified our reluctance to accept the reality of the Callisto absorptions. The earlier spectra are reproduced here for their historical interest, in part because of the quite large effort expended both at the telescope and in the reductions. The superiority of the new spectra is due to extensive work by Drs. Dekkers and Fink on the interferometer itself, which increased its signal-to-noise ratio by a factor of about 4, corresponding to a gain of 16 in observing time.

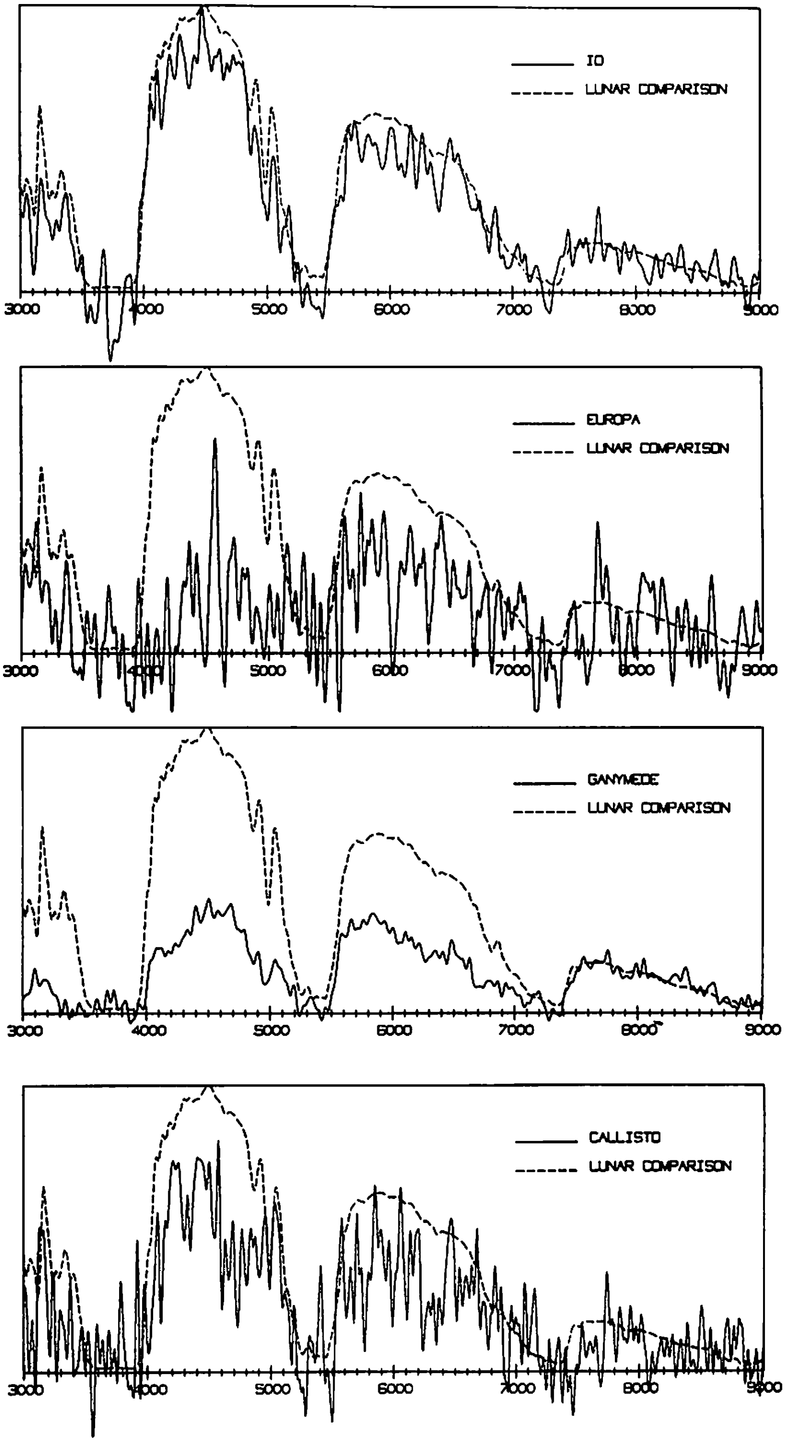

Figure 2 Jupiter Satellites, spectral resolution 80 cm^{-1}, 3.3-1.1μ (scale in wave numbers). (Provisional)

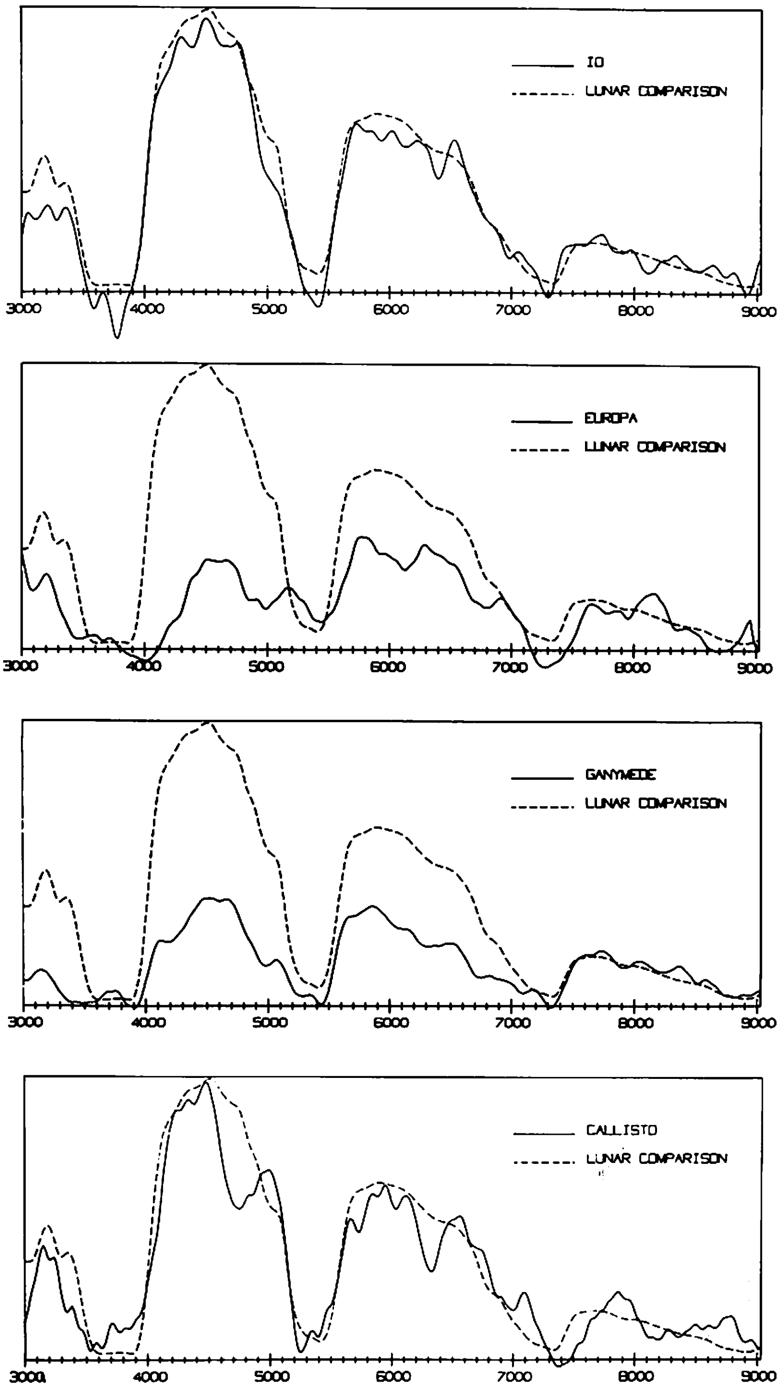

Figure 3 Jupiter Satellites, spectral resolution 200 cm^{-1}, 3.3-1.1μ (scale in wave numbers). (Provisional)

The albedo curve obtained by Wamsteker for the shorter wavelengths, 0.3-1.1μ (*LPL Comm. No. 167*), is compatible with the reflection curve of *sulfur*, as pointed out in Wamsteker's paper. So is the high and uniform albedo from 1-4μ. The observations at 3.5μ and 5μ by Gillett *et al.* (1970) are also consistent with Io being covered by sulfur. *No other substance has been found that explains the entire range, 0.3-5μ, so well.* For laboratory comparisons reference is made to *LPL Communication No. 184* by Fr. Sill and *No. 185* by Fink and Burk. The *only deviation from the smooth sulfur reflection curve occurs around 0.56μ*, where a 10%-deep absorption feature is noted extending from 0.50-0.62μ. Wamsteker called attention to the proximity of this feature to a band by $NH_4 \cdot HS$ at 0.65μ, seen in the laboratory curves of Fr. Sill's publication. However, the systematic drop, longward of 1μ and the narrower strong absorptions near 2μ, both absent from Io, cast doubt on a substantial admixture of $NH_4 \cdot HS$.

2. Other Observations

In the following *Communication* the discovery of the russet color of the darkish polar caps of Io is announced by R. B. Minton. The polar-cap colors appear to be close to that of the Jupiter Red Spot, which we have tentatively attributed to ammonium polysulfides. We are awaiting spectra of the Red Spot 0.3-4μ before this matter can be resolved. Still, the integrated spectrum of Io does not appear to contain an appreciable admixture of the type of spectrum that Fr. Sill found for ammonium polysulfides in the laboratory. Even the Io band at 0.56μ does not agree well with the laboratory absorption at 0.65μ.

Binder and Cruikshank (1964) discovered a brightening of Io immediately following a total eclipse by the planet. The observations were made in blue light (λ4500Å) and the most natural explanation would appear to be that *the sulfur deposit on the satellite became white at the very low temperatures during the eclipse*, 90°-100°K (Morrison and Cruikshank 1973). If this hypothesis is correct, the post-eclipse effect should be nearly absent in red light, and be maximum around 4000Å. Actually, T. Johnson (1971) finds the effect on Io larger at λ4350 than at λ5600Å; but more data, including at 0.40μ, are needed before a clear answer is at hand.

Morrison and Cruikshank (1973, p. 232) conclude from their eclipse observations at 20μ that Io and the other satellites have a low-density surface layer only a few mm thick of very low conductivity, below which lies a layer of much greater conductivity. They assume the upper layer of all four satellites to be *ice* mixed to varying degrees with *rock powder*. We believe a thin *S* deposit to be better in accord with the spectral data. It could be due to H_2S exhalations, with the solar UV decomposing the gas and causing a deposit of S, with H escaping. If the Red Spot is indeed found to be $NH_4 \cdot xS$, this may be the composition of the Io polar cap deposits as well. Fr. Sill points out that such a deposit could be due to occasional NH_3 exhalations causing NH_3 *ice* deposits on the *cold poles*; with H_2S exhalations causing the NH_3 ice to form $NH_4 \cdot HS$; which would turn to the polysulfide by the solar UV radiations, much as supposedly occurs in the Jupiter Red Spot and other russet-colored Jupiter clouds. The polar caps are then due in the first place to the low vapor pressure of NH_3 being able to deposit its ice only under temperatures lower than about 100°K. The equatorial NH_3 would decompose and escape; the equatorial H_2S cause the sulfur coating. I am indebted to Fr. Sill for a clarifying discussion on the subject of this paragraph. A preliminary announcement on the Io polar caps is found in *Sky and Telescope*, October 1973, p. 228.

Hansen (1973) similarly concludes that JI, JII, JIII require a two-layer model to satisfy his 1971 eclipse observations made at 8-14μ. He stresses, however, that a difference is indicated for the thin upper layers of JI, as compared to the other two satellites, in the sense of a lower conductivity for Io. A composition difference is certainly indicated by the spectra.

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