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Color Photometry of Surface Features on Ganymede and Callisto

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Voyager imaging data demonstrate that the scattering properties ("phase curves") of all major terrain types on Ganymede and Callisto are not significantly wavelength dependent between 0.4 and 0.6 μm. Our data suggest that the phase curves may be slightly steeper at the shorter wavelengths, consistent with the trend of telescopic observations near opposition. However, the differences are small and entirely within the uncertainties of our analysis. Our result indicates that the phase integrals (0.8 for Ganymede and 0.6 for Callisto) derived by S. W. Squyres and J. Veverka [*Icarus* **46**, 137–155 (1981)] from the abundant Voyager clear filter observations are reliable measures of the radiometric phase integrals. The corresponding values of the Bond albedo turn out to be 0.35 for Ganymede and 0.11 for Callisto.

INTRODUCTION

Using Voyager clear filter data, Squyres and Veverka (1981) have shown that the major photometric units on Ganymede and Callisto have scattering properties that can be described very well, within the constraints of available measurements, by a lunar-like photometric function of the form

$$I(i,\epsilon,\alpha) = F[\mu_0/(\mu_0 + \mu)]f(\alpha), \quad (1)$$

where I is the intensity of the scattered light for an incidence angle i, an emission angle ϵ, and a phase angle α. The incident solar flux is πF and $\mu_0 = \cos i$ and $\mu = \cos \epsilon$.

Here we investigate the extent to which the photometric phase function $f(\alpha)$ depends on wavelength between approximately 0.4 and 0.6 μm. In going from 0.4 to 0.6 μm, the disk-integrated normal reflectance [$r_n = f(0°)/2$] of both Ganymede and Callisto increase by a factor of 1.4 (Johnson and Pilcher, 1977). Yet, we will show that at least between phase angles of 50 and 90° the Voyager data indicate very little or no wavelength dependence of $f(\alpha)$. Combined with the negligibly small wavelength dependence of disk-integrated phase curves determined by telescopic observers near opposition (Morrison and Morrison, 1977; Veverka, 1977), this suggests that the phase integrals of Ganymede and Callisto estimated by Squyres and Veverka (1981) on the basis of clear filter data do not require any significant adjustment for variations with wavelength in calculating radiometric Bond albedos. Additionally, the result means that in constructing global color maps (e.g., McCord *et al.*, 1982) the same photometric law can be applied to images taken with all Voyager filters, greatly simplifying the task.

We note that recently Danielson *et al.* (1981) have proposed a recalibration of the Voyager photometric scale. To bring the absolute values of $f(\alpha)$ quoted here in correspondence with their proposed recalibration would require that all our values be multiplied by constant factors, namely, 0.878 for clear images, 0.737 for violet, and 1.03 for orange.

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AVAILABLE DATA

The best Voyager data set for the study of the wavelength dependence of $f(\alpha)$ consists of violet, clear, and orange triplets taken by the Voyager 1 wide-angle camera between phase angles of 47 and 85° for Ganymede, and between 49 and 85° for Callisto (Table I). The effective wavelength of the Voyager wide-angle camera violet filter is approximately 0.4 μm; that of the orange filter is about 0.6 μm (Danielson *et al.*, 1981). The passband of the clear filter extends from about 0.3 to 0.6 μm, centered near 0.47 μm [cf. Fig. 1 of Squyres and Veverka (1981)]. We note that the clear filter images used in the present investigation are not identical with those used by Squyres and Veverka (1981). Therefore the clear filter information derived here is complementary to that derived in the previous paper.

TABLE I

IMAGES USED FOR COLOR PHOTOMETRY[a]

Picture number	Phase angle (°)	Filter
Ganymede		
740J1 + 000	47	Clear
742J1 + 000	48	Violet
746J1 + 000	48	Orange
870J1 + 000	59	Clear
872J1 + 000	59	Violet
876J1 + 000	59	Orange
952J1 + 000	75	Clear
954J1 + 000	75	Violet
958J1 + 000	75	Orange
988J1 + 000	85	Clear
990J1 + 000	85	Violet
994J1 + 000	85	Orange
Callisto		
142J1 + 001	49	Clear
166J1 + 001	51	Violet
174J1 + 0001	52	Orange
320J1 + 001	75	Clear
322J1 + 001	75	Violet
326J1 + 001	76	Orange
356J1 + 001	83	Clear
358J1 + 001	84	Violet
364J1 + 001	85	Orange

[a] All images were obtained by the Voyager 1 wide-angle camera.

The color triplets analyzed cover a limited range of longitudes (Figs. 1 and 2)—essentially the Jupiter-facing hemispheres of the two satellites. This limited longitude coverage probably does not bias our conclusions. The disk-integrated lightcurves of the two satellites are well known both as a function of wavelength and orbital phase (Morrison and Morrison, 1977). Between 0.4 and 0.6 μm these data show that, at the small phase angles observable from Earth, the trailing side of Ganymede is slightly redder than the leading side; the reverse is true for Callisto. However, the differences are small, amounting to 5% or less.

GANYMEDE

Following the procedure of Squyres and Veverka (1981), four separate photometric

TABLE II

RELATIVE REFLECTANCE OF POINTS EXAMINED ON GANYMEDE[a]

Point	Terrain type	Phase function $f(47°)$		
		Violet	Clear	Orange
A	Grooved terrain	0.563	0.589	0.577
B	Grooved terrain	0.550	0.587	0.577
C	Grooved terrain	0.493	0.533	0.546
D	Grooved terrain	0.454	0.502	0.518
E	Grooved terrain	0.609	0.628	0.661
F	Grooved terrain	0.503	0.540	0.533
G	Cratered terrain	0.359	0.384	0.393
H	Cratered terrain	0.398	0.443	0.445
I	Cratered terrain	0.371	0.398	0.359
J	Cratered terrain	0.459	0.496	0.512
K	Cratered terrain	0.498	0.535	0.530
L	Cratered terrain	0.482	0.505	0.510
M	Bright crater	0.806	0.812	0.710
N	Bright crater	0.693	0.732	0.673
O	Bright crater	0.620	0.661	0.644
P	Bright crater	0.759	0.783	0.751
Q	Bright crater	0.564	0.509	0.524
R	Bright crater	0.593	0.600	0.553
S	Polar cap	0.588	0.593	0.536
T	Polar cap	0.724	0.723	0.674
U	Polar cap	0.730	0.737	0.696
V	Polar cap	0.731	0.740	0.699

[a] All observations from the Voyager 1 wide angle. The phase function $f(\alpha)$ is given by $(I/F)/[\mu_0/(\mu_0 + \mu)]$. See Eq. (1).

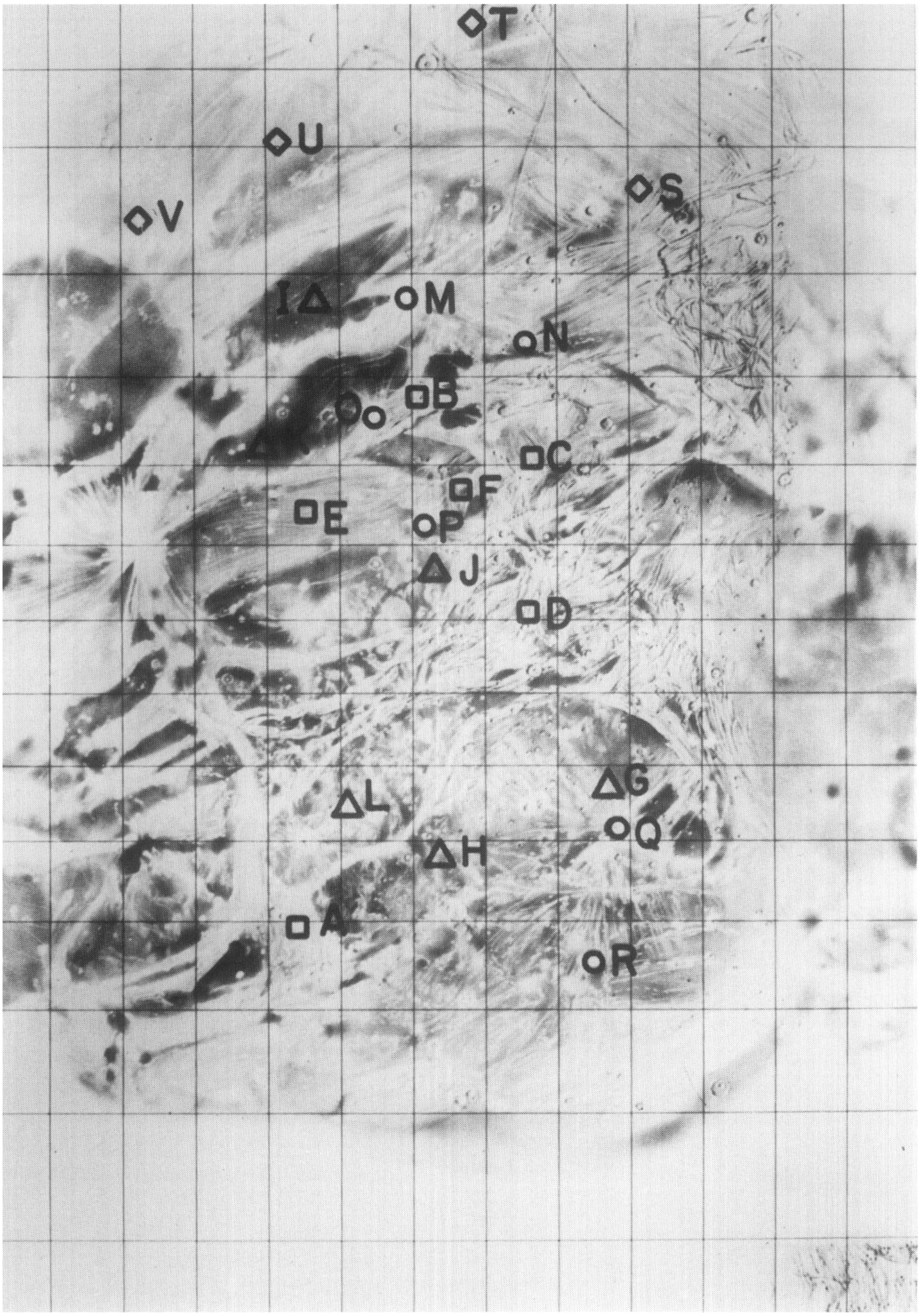

FIG. 1. Points selected for color photometry on Ganymede: cratered terrain (triangles), grooved terrain (squares), polar caps (diamonds), and bright craters (circles).

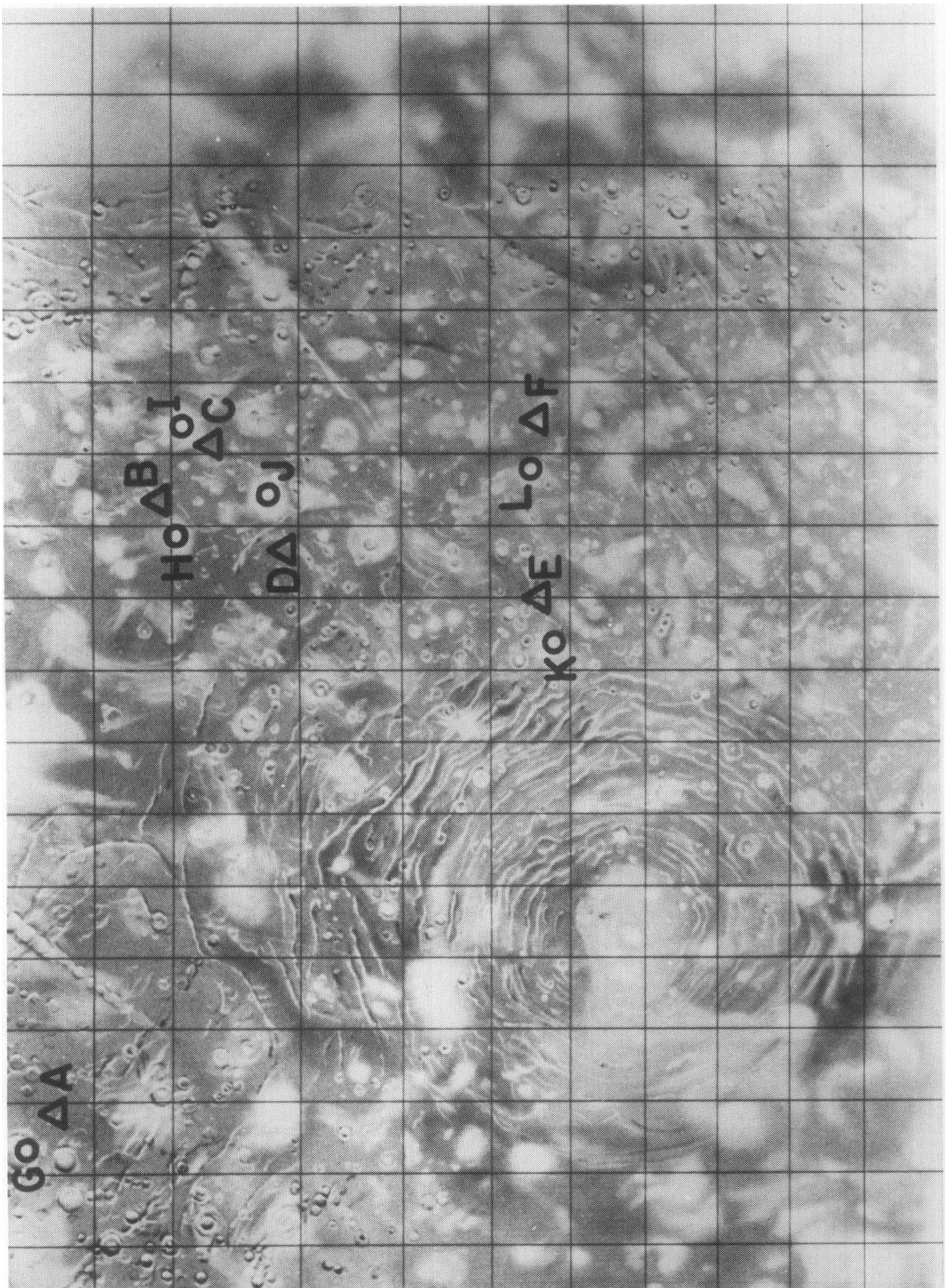

FIG. 2. Points selected for color photometry of Callisto: cratered terrain (triangles) and bright craters (circles).

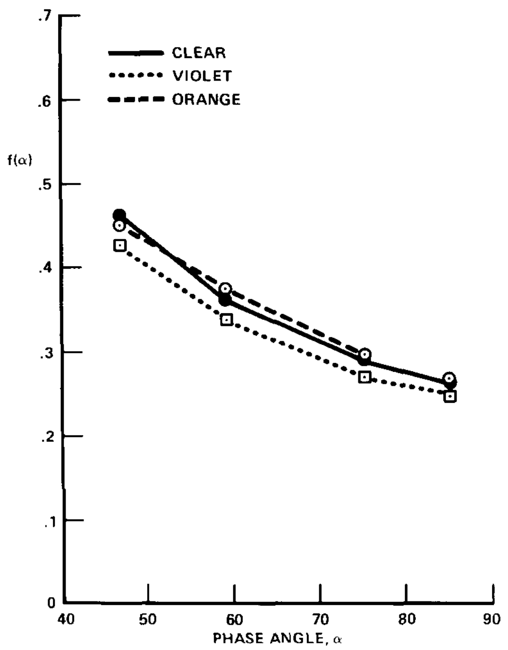

FIG. 3. Average Voyager 1 wide-angle color phase curves for Ganymede cratered terrain.

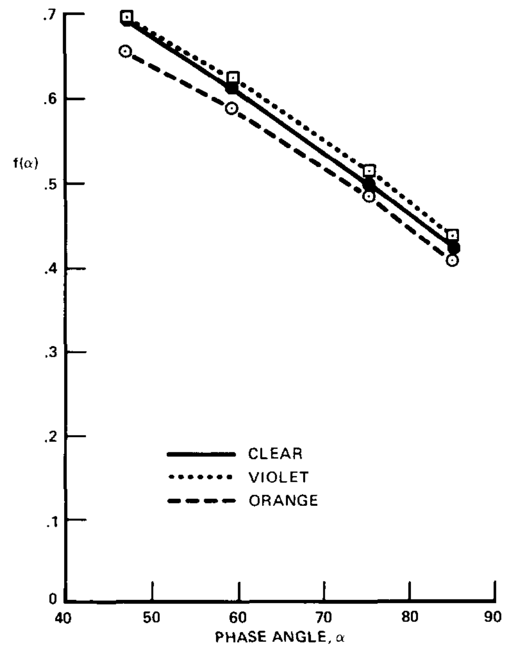

FIG. 5. Average Voyager 1 wide-angle color phase curves for Ganymede polar caps.

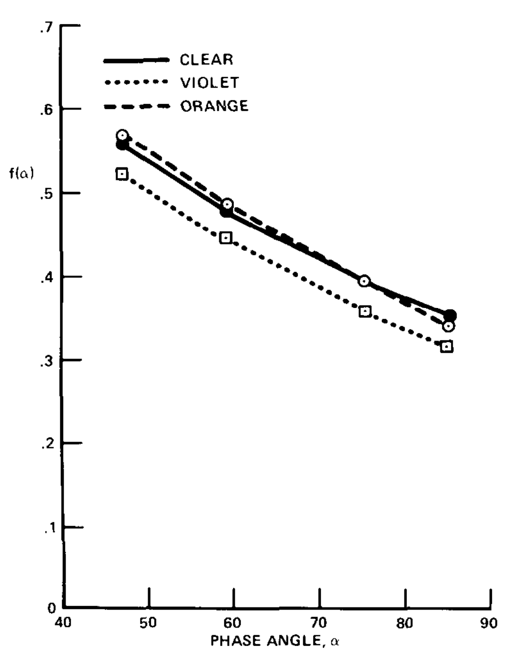

FIG. 4. Average Voyager 1 wide-angle color phase curves for Ganymede grooved terrain.

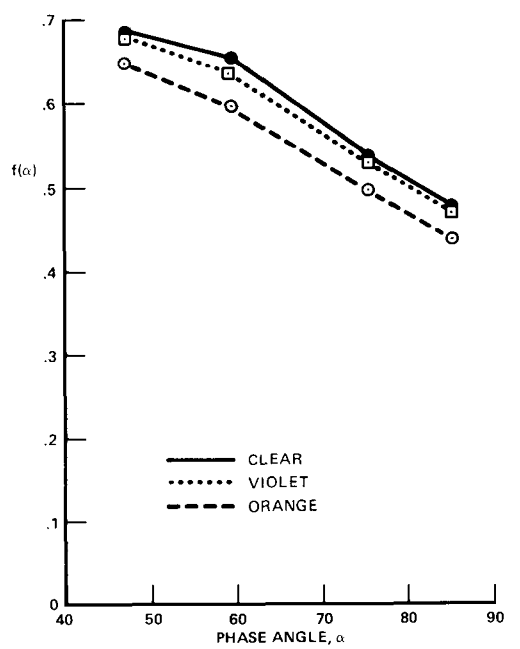

FIG. 6. Average Voyager 1 wide-angle color phase curves for Ganymede bright craters.

units on this satellite were considered: cratered terrain, grooved terrain, polar caps, and bright craters. In all, 22 individual regions were studied (Fig. 1, Table II) between phase angles of 47 and 85°. In the clear filter the $f(\alpha)$'s derived were found to agree closely with those for the same terrain determined in the more extensive earlier study (Squyres and Veverka, 1981). For no individual region was a significant wavelength dependence to the shape of $f(\alpha)$ observed. Therefore, to improve the signal-to-noise ratio the data were averaged for each photometric unit. The resulting averaged curves are shown in Figs. 3–6. The conclusion is that the shapes of the $f(\alpha)$ curves are identical in all three filters, within the accuracy of the data and reduction technique. To quantify this assertion a quadratic polynomial of the form

$$f(\alpha) = a + b\alpha + c\alpha^2 \qquad (2)$$

was fitted to the data for the cratered and grooved terrains (Figs. 3 and 4). The results of these fits are given in Table III. While there is a trend for the curves to be slightly steeper in the violet than in the orange—consistent with the universal tendency of lower albedos being associated with larger color phase coefficients—the difference lies entirely within the error bars.

Finally, the data were also reduced in a disk-integrated form (Fig. 7), and again confirm the conclusion that no wavelength dependence of the shape of $f(\alpha)$ can be demonstrated for Ganymede over this range of phase angles within the accuracy of the data.

Table II lists the absolute values of $f(\alpha)$ at $\alpha = 47°$ in the three filters for the 22 regions investigated. These values give directly the relative reflectances of these units at this phase angle. Since the major conclusion here is that $f(\alpha)$ is not measurably dependent on wavelength between 0.4 and 0.6 μm and between $\alpha = 47$ and 85°, the best $f(\alpha)$ available currently—that determined for the clear filter by Squyres and Veverka

TABLE III

FITS TO GANYMEDE COLOR PHASE CURVES[a]

	Violet	Clear	Orange
		Cratered terrain	
$(b \pm \sigma_b) \times 10$	-0.163 ± 0.055	-0.174 ± 0.087	-0.118 ± 0.050
$(c \pm \sigma_c) \times 10^4$	0.849 ± 0.426	0.930 ± 0.646	0.509 ± 0.345
		Grooved terrain	
$(b \pm \sigma_b) \times 10$	-0.102 ± 0.041	-0.103 ± 0.028	-0.089 ± 0.047
$(c \pm \sigma_c) \times 10^4$	0.337 ± 0.291	0.367 ± 0.195	0.231 ± 0.330

[a] Data in Figs. 2 and 3 fitted to $f(\alpha) = a + b\alpha + c\alpha^2$ (α in degrees).

(1981)—can be used to calulate relative reflectances at other phase angles within the range in question. We stress again that the $f(\alpha)$'s determined here for the clear filter are in good agreement with those derived by Squyres and Veverka (1981). However, the clear filter $f(\alpha)$'s determined in the earlier study were derived from a considerably more extensive data base.

Since the phase curves for the bright craters show the largest diversity, and since the craters studied here are not the same as those studied by Squyres and Veverka

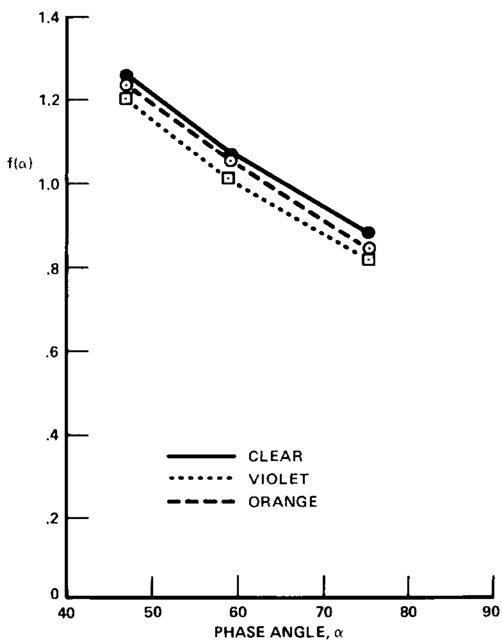

FIG. 7. Disk-averaged Voyager 1 wide-angle color phase curves, $f(\alpha)$, for Ganymede.

(1981), the individual clear filter phase curves for the bright craters listed in Table II are shown in Fig. 8.

CALLISTO

On Callisto a dozen individual regions were studied (Fig. 2, Table IV), equally divided between the two photometric units discussed by Squyres and Veverka (1981): cratered terrain and bright craters. Again, the individual bright craters investigated here differ from those in the previous study. The individual clear filter phase curves of the six bright craters listed in Table IV are shown in Fig. 8.

The Callisto color data cover a range of phase angles from $\alpha = 49$ to 85°. As in the case of Ganymede, no significant wavelength dependence in the shapes of the individual or average $f(\alpha)$ curves (Figs. 9 and 10) is detectable. Since the phase curves are essentially linear over the phase angle range in question, a linear function of the form

$$f(\alpha) = a + b\alpha \quad (3)$$

was fitted to the data in Figs. 9 and 10. The results, summarized in Table V, show that while numerically the slopes are slightly higher in the violet than in the orange, again the differences lie entirely within the error bars. Similar conclusions hold for the disk-integrated data shown in Fig. 11.

As in the case of Ganymede, the Voyager data contain no evidence of a measurable wavelength dependence of the shape of $f(\alpha)$.

Table IV lists the absolute values of $f(\alpha)$ at $\alpha \simeq 50°$, in the three filters, for the twelve Callisto regions investigated (Figs. 2).

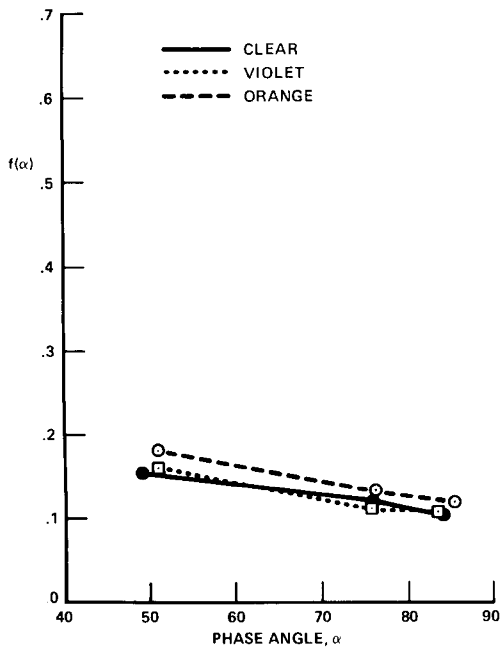

FIG. 9. Average Voyager 1 wide-angle color phase curves for Callisto cratered terrain.

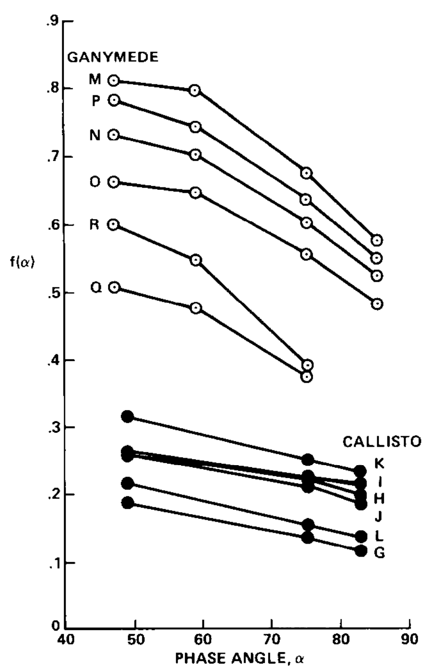

FIG. 8. Voyager 1 wide-angle clear phase curves for the individual bright craters on Ganymede and Callisto investigated in this study. Locations are shown in Figs. 1 and 2.

DISCUSSION

One conclusion of immediate importance is that the phase integral q (Harris, 1961; Veverka, 1977) for both bodies is not strongly wavelength dependent between 0.4 and 0.6 μm. Since this is precisely the spectral region over which the most dra-

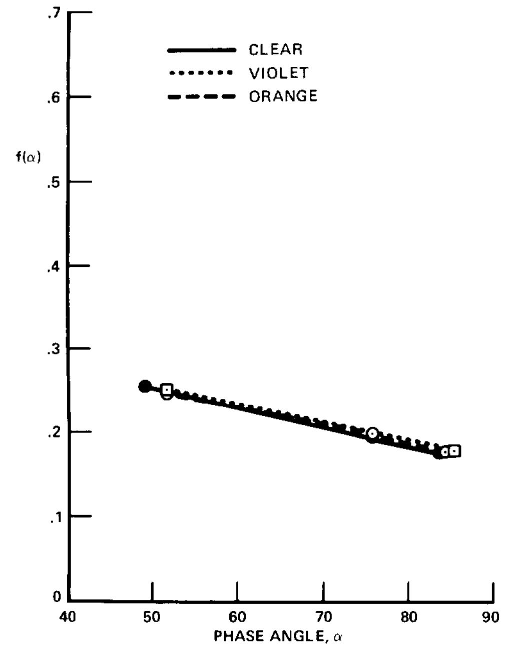

FIG. 10. Average Voyager 1 wide-angle color phase curves for Callisto bright craters.

matic spectral reflectance variations occur (Johnson and Pilcher, 1977), one would expect the wavelength dependence of $f(\alpha)$, and hence of q, to be at a maximum here. Thus the phase integrals and Bond albedos derived for Ganymede and Callisto by

TABLE IV

RELATIVE REFLECTANCE OF POINTS EXAMINED ON CALLISTO[a]

Point	Terrain type	Phase function $f(50°)$		
		Violet	Clear	Orange
A	Cratered terrain	0.122	0.126	0.141
B	Cratered terrain	0.205	0.202	0.215
C	Cratered terrain	0.171	0.172	0.217
D	Cratered terrain	0.152	0.167	0.176
E	Cratered terrain	0.139	0.145	0.147
F	Cratered terrain	0.139	0.152	0.157
G	Bright crater	0.180	0.188	0.193
H	Bright crater	0.251	0.262	0.247
I	Bright crater	0.269	0.259	0.260
J	Bright crater	0.256	0.260	0.249
K	Bright crater	0.311	0.315	0.296
L	Bright crater	0.194	0.217	0.197

[a] All observations from the Voyager 1 wide angle. The phase function $f(\alpha)$ is given by $(I/F)/[\nu_0/(\mu_0 + \mu)]$. See Eq. (1).

TABLE V

FITS TO CALLISTO COLOR PHASE CURVES[a]

	Violet	Clear	Orange
	Cratered terrain		
$(b \pm \sigma_b) \times 10^3$	-1.763 ± 0.460	-1.667 ± 0.483	-1.629 ± 0.551
	Bright craters		
$(b \pm \sigma_b) \times 10^3$	-2.110 ± 0.652	-2.114 ± 0.681	-2.051 ± 0.753

[a] Data in Figs. 9 and 10 fitted to $f(\alpha) = a + b\alpha$.

Squyres and Veverka (1981) on the basis of the Voyager clear filter phase data and the telescopically observed spectral reflectance curve at low phase angles should be accurate to probably better than ±10%. Squyres and Veverka (1981) found q = 0.8 and 0.6 for Ganymede and Callisto, respectively, in the Voyager clear filter, with an uncertainty of about ±0.1 or less.

Assuming that these values of q are close to the radiometric ones (in other words, that q is not strongly dependent on wavelength), the average Bond albedos of Gany-

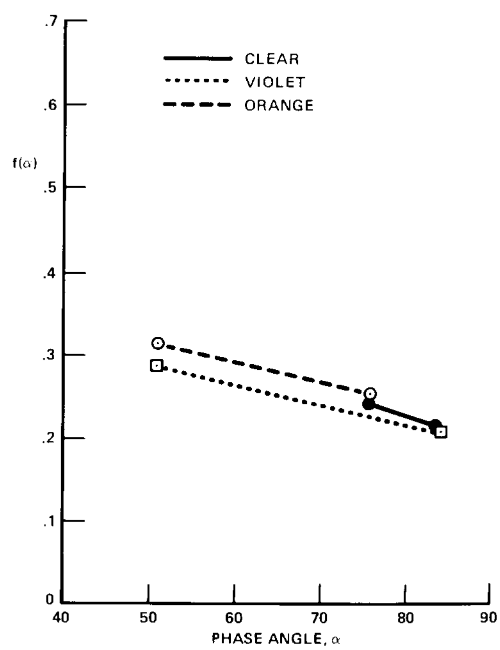

FIG. 11. Disk-averaged Voyager 1 wide-angle color phase curves, $f(\alpha)$, for Callisto.

mede and Callisto are 0.35 and 0.11, respectively [rather than a Bond albedo of 0.13 for Callisto, as was reported by Squyres and Veverka (1981)].

The negligible wavelength dependence of $f(\alpha)$ between 0.4 and 0.6 μm found from the Voyager observations is consistent with available Earth-based observations between $\alpha = 0$ and $12°$. According to data reviewed by Veverka (1977), the color phase coefficient $d(v - y)/d\alpha$ is about 0.003 mag/deg for Ganymede and 0.004 mag/deg for Callisto. (The effective wavelengths of the Stromgren v and y filters are about 0.41 and 0.55 μm, respectively.) Thus, even if a similar color dependence held over the range of phase angles covered by the Voyager color data, one would expect to see a magnitude difference of

$$\Delta m(v - y) \simeq 40 \times 0.003 \simeq 0.1$$

between $\alpha = 50$ and $90°$, so $f(90°)/f(50°)$ might be no more than 10% lower in the violet than in the orange. Such a small possible difference is consistent with the data presented above.

The very slight color dependence of Ganymede's phase coefficient can be easily understood in terms of a naive model which considers the surface to be made up of two photometric elements: (1) clean water frost, and (2) a dark, possibly carbonaceous material. Assuming that the frost has a reflectance of 0.8 and the dark material 0.05, the average reflectance of Ganymede of about 0.5 means that about 20 times as much light comes from the frost as from the dark component. The clean ice, being spectrally neutral, should have a negligibly small color dependence to its phase coefficient. A typical value for the color phase coefficient of carbonaceous chondrites is $d0.4–0.6\ \mu m)/d\alpha \simeq 0.001–0.002$ mag/deg (Gradie and Veverka, 1982). The surface material of the Moon has a value of $d(0.4–0.6\ \mu m)/d\alpha$ of roughly 0.001 mag/deg (Lane and Irvine, 1973). Thus Ganymede cannot have a strongly color-dependent $f(\alpha)$.

In the case of Callisto, a similar argument indicates that about four times as much light would come from the frost and the color dependence of the phase coefficient should be only one-fourth that of pure carbonaceous materials. The model on which this discussion is based is too naive to describe the true nature of the satellite surfaces or to reproduce accurately the observed values of $d(0.4–0.6\ \mu m)/d\alpha$ near opposition (Veverka, 1971). However, the model is sufficient to rationalize why the shape of $f(\alpha)$ is only very weakly dependent on wavelength for both Ganymede and Callisto.

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