CALLISTO'S REGOLITH: A BETTER ESTIMATE OF THE ICE/SILICATE RATIO.
P. Helfenstein, J. Veverka, and J. Hillier, Center for Radiophysics and Space Research, Cornell University, Ithaca, NY 14850.

A valuable outgrowth from modern planetary photometry is its potential use for estimating mineral abundances in multi-component regoliths. The most frequently studied multi-particle mixing equation represents the single scattering albedo, $\varpi_{0,m}$, of a particulate mixture as a weighted average of j end-members whose single-scattering albedos, $\varpi_{0,j}$ are presumably known. If N_j is the volume density of particles of type j, and σ_j is the corresponding particle cross section, then $\varpi_{0,m} = \sum N_j\sigma_j\varpi_{0,j}/\sum N_j\sigma_j$ [Eqn. 1]. Estimates $\varpi_{0,m}$ and $\varpi_{0,j}$ are generally obtained by application of Hapke's photometric model[1,2,3] to reflectance measurements of planetary surfaces and/or laboratory analogs. Experimental efforts to verify the mixing model[4,5] demonstrate that it successfully predicts mixing ratios in simple two component systems when dark (opaque) particles are mixed with other dark (opaque) particles and when bright (transparent) particles are mixed with other bright (transparent) particles. The mixing equation appears to work less well for predicting ratios of dark opaque particles mixed with bright transparent particles—a particle mixing scheme that is especially important for the surfaces of outer planet satellites for which dark (silicate) grains may be mixed with bright (icy) particles.

The present study shows that the inadequacy of Eqn. 1 to model mixtures of opaque with transparent particles is likely due to unreliable estimates of single scattering albedo (ϖ_0) obtained from Hapke's model when unrealistic particle phase functions are adopted. A particle phase function, $P(\alpha)$, is an analytic expression that describes how the intensity of singly scattered light from a particle, $\varpi_0 P(\alpha)/4\pi$, varies with phase angle α. It has been known for a long time that isolated, irregularly-shaped particles tend to have scattering functions which exhibit both backward and forward scattering lobes that are typically asymmetric. Only recently, however, have studies confirmed that concurrently strong forward- and backscattering persist when particles are in mutual contact, as in a planetary regolith[6,7]. These studies provide ample evidence that the simple 1-term Henyey-Greenstein particle phase function[8] most often used in Hapke's model is inadequate to realistically realistically the scattering behavior of particulate surfaces at all phase angles.

$P(\alpha)$ and ϖ_0 are fundamentally related: Particles that strongly forward scatter light have large ϖ_0's, and conversely, those lacking a significant forward scattering lobe have small ϖ_0's. It is thus reasonable to expect that unreliable estimates of ϖ_0 will result from the use of unrealistic particle phase functions in Hapke's photometric model. Such unreliable ϖ_0's may subsequently yield erroneous estimates of particulate mixing ratios when results are applied to Eqn. 1. It is likely that errors would be largest for mixtures of end-members whose albedos differ strongly. To investigate this hypothesis, we follow the approach of earlier workers[7,9] and modify Hapke's equation to include double Henyey-Greenstein particle phase function[10] that is known to accurately model the scattering behaviors of isolated large irregular particles[11]. This scattering function is a linear combination of two one-term Henyey-Greenstein functions and uses three variables; g_1 and g_2 are asymmetry parameters that model the angular shapes of backward and forward scattering lobes, respectively, and a linear coefficient f that partitions the relative contributions of each lobe.

We applied this model to detailed photometric observations of the Jovian moon Callisto—a good planetary example for which regolith may be a mixture of dark (silicate) grains and bright (icy) particles—and compared our results to earlier estimates that employed a one-

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term Henyey-Greenstein function (Table 1). Our data set combines V-filter Earthbased telescopic observations[12,13] covering $0.3° \leq \alpha \leq 11.2°$ with lightcurve-corrected whole-disk data covering $8.6° \leq \alpha \leq 143.4°$ that we derived from radiometrically calibrated Voyager clear-filter images ($\lambda = 0.49 \mu m$). We also required the fits to predict disk-resolved limb-darkening behavior modeled from Voyager observations by Buratti[14].

Our least-squares fits (Table 1) yield $\varpi_0 = 0.76 \pm 0.03$, compared to $\varpi_0 = 0.44 \pm 0.01$ obtained with a one-term Henyey-Greenstein function model[14]. Allowing for the presence of a significant forward-scattering lobe in $P(\alpha)$ yields a ϖ_0 that is 73% larger than earlier estimates based on a scattering function that modeled only the backscattering lobe. If we assume that Callisto's surface is a mixture of transparent frost grains[15] ($\varpi_0 \approx 1.0$, $\rho = 0.9$ g/cm^3) and dark (silicate) grains like those on C-type asteroids[16] and Phobos[17] ($\varpi_0 \approx 0.07$, $\rho = 2.5$ g/cm^3), then our value of ϖ_0 predicts silicate:ice ratio of 26:74 by volume and a solid (compacted) density of 1.3 g/cm^3. Such a mixture would be buoyant on an object with Callisto's mean density (1.8 g/cm^3). In contrast, the same calculation using $\varpi_0 = 0.44$ gives silicate:ice of about 60:40 and a solid density of 1.9 gm/cm^3—material that would be vertically unstable on Callisto. We conclude that meaningful mineral abundance estimates for mixtures of dark grains and bright particles can be obtained with Eqn. 1 if realistic particle phase function models are adopted.

Table 1: CALLISTO REGOLITH ICE FRACTION

	PARTICLE PHASE FUNCTION	ϖ_0	ICE FRACTION	SOLID DENSITY
STANDARD MODEL (single H-G)	$g_1 = -0.20 \pm 0.03$	0.44 ± 0.01	40%	1.9 g/cm^3
NEW MODEL (double H-G)	$g_1 = -0.41 \pm 0.10$ $g_2 = +0.37 \pm 0.30$ $f = 0.80 \pm 0.25$	0.76 ± 0.03	74%	1.3 g/cm^3

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