PHOTOMETRICALLY DETERMINED SURFACE PHYSICAL PROPERTIES OF TERRAINS ON GANYMEDE. Paul Helfenstein, Dept. of Geological Sciences, Brown University, Providence, RI 02192 and Center for Radiophysics and Space Research, Cornell University, Ithaca, NY 14850.

Geological processes which affect the origin and subsequent evolution of different terrains on a planetary surface are often recorded in physical properties of terrain regoliths. Hapke's (1) photometric equation provides a means of determining five parameters representing different regolith physical properties from observations of surface reflectance as a function of changing illumination and viewing geometry. These five properties are average particle single scattering albedo (w), a surface compaction parameter related to the regolith porosity and rate of compaction with depth (h), Legendre coefficients of a particle phase function which describe the state of internal transparency and external texture of average regolith particles (b and c), and an average topographic slope angle ($\bar{\theta}$) which describes the subpixel scale macroscopic roughness of the surface. Variations of these properties between different terrains or even superficially similar terrains provide a meaningful framework for terrain classification (2), while their interpretation for a particular terrain in the context of possible geological processes can reveal subtle clues about geological evolution. Preliminary parameter sets (2) reported for specific terrain samples in the JG-4 quadrangle of Ganymede were found to be useful for geological interpretation in a relative sense, however, their absolute values were unreliable because they were derived from a relatively narrow range of illumination and viewing conditions. A subsequent study (3) provided reliable average values of the five parameters for global collections of both polar and non-polar dark terrain and bright terrain photometric measurements obtained from radiometrically corrected Voyager clear-filter images.

The average global values of Hapke's parameters (3) cannot represent important possible variations which may distinguish subclasses within each of Ganymede's two principal terrains (dark and bright terrains). The identification of such subclasses are vital to understanding Ganymede's geological evolution, especially if examples of terrains intermediate in development between dark and bright terrains (as well as their accompanying physical properties) can be isolated. The present investigation has succeeded in developing a criterion for separating subclasses of dark and bright terrains on the basis of systematic variations in photometric behavior of individual sample terrains comprising the global collections used in (3). The global data bases for (3) consisted of reflectance measurements and corresponding photometric angles for 41 examples of dark terrain and 34 examples of bright terrain. Reflectance measurements for each terrain example were collected over as wide a range of phase angle (g) as allowed by Voyager coverage, however, few individual terrain examples yielded measurements over a large enough phase angle range to determine parameters for individual examples reliably. Fortunately, enough phase angle overlap existed between different examples of similar terrains that relatively uniform photometric behavior for a number of different terrain subclasses could be isolated. A graphical approach was devised for photometric comparison of individual terrain examples in which measured reflectance of a particular terrain example at a particular phase angle was normalized by the predicted reflectance of the corresponding average non-polar dark or bright terrain (3) under the same illumination and viewing conditions. Plots of the normalized reflectance as a function of phase angle for each terrain sample were created and compared. Patterns were identified in each plot for which measured reflectances could vary systematically less than, equal to, or greater than prediced average over different phase angle ranges. Reflectance data for individual terrain examples having similar photometric behavior over their overlap phase angles were combined into groups. Hapke parameters were then reduced (3) for each group that contained a relatively complete range of phase angle coverage. Results reported in Table 1 identify the existence of at least six varieties of dark terrain and eight varieties of bright terrain.

Comparison of Table 1 values with the global non-polar average values for dark ($w=0.61$, $h=0.64$, $b=0.40$, $c=0.17$, $\bar{\theta}=25.1^\circ$) and bright terrains ($w=0.61$, $h=0.20$, $b=1.22$, $c=0.22$, $\bar{\theta}=2.7^\circ$) from (3) shows that average global parameters poorly represent the large variety of regolith properties for different Ganymede terrains. Although, on an average, dark and bright terrains have similar single scattering albedoes, Table 1 shows that these are generally averages for large ranges ($0.42 \leq w \leq 0.72$ for dark terrain and $0.58 \leq w \leq 0.90$ for bright terrain). If w may be used to indicate the relative abundance of two materials in a particulate two-component mixture of ice and silicates, then the large overlap in these ranges suggests that there are indeed examples of dark and bright terrains which may have similar silicate-to-ice ratios. The w end-members for dark terrains are nevertheless significantly lower than their bright terrain counterparts suggesting that some dark terrains contain higher silicate-to-ice ratios than any examples of bright terrains, and also that some bright terrains have lower silicate-to-ice ratios than any examples of dark terrains. Average values of h for dark and bright terrains are likewise derived from large ranges ($0.15 \leq h \leq 1.04$ for dark terrains and $0.10 \leq h \leq 0.76$ for bright terrains). The interpretation of regolith compaction as a function of h in (3) made on the basis of an earlier work by Hapke (4) is inaccurate and has been replaced by a new interpretation (5) in which increasing values of h correspond to increasing states of compaction and/or increasing rate of compaction with depth in the regolith. With the new interpretation, the average dark terrain $h=0.64$ and bright terrain $h=0.20$ suggests that bright terrain is generally more porous than dark terrain as well as lunar regolith ($h=0.4$ (6)). Most dark terrains are either very much compacted in comparison to lunar soils or else compact very quickly with depth, consistent with thermal intertia measurements for Ganymede (7) and possible greater accumulation of pore-migrating water molecules (8) in presumably older dark terrain soils. Again, Table 1 shows the occurence of many examples of dark and bright terrain regoliths in similar states of compaction. The b and c parameters are best interpreted from plots of the particle phase function, $P(g)=1 + b \cos(g) + c\ [1.5 \cos^2(g)-0.5]$. Close examination of these plots (not shown) for each group in Table 1 showed that both dark and bright terrain regolith particles were generally more strongly backscattering than forward scattering. Dark terrain Group 6 and bright terrain Groups 2, 3, 7 and 8 exhibited well-defined forward scattering lobes, however, indicating that average particles in these terrains were considerably more transparent than those in the remaining terrains. Many of the terrain samples comprising these groups were found lie within Ganymede's polar shroud, consistent with the likely greater occurence of transparent ice particles at polar latitudes. In general, greater particle transparency was found to accompany larger single scattering albedo, also consistent with polar accumulations of ice particles. Macroscopic roughness for dark terrains ($0.3° \leq \bar{\theta} \leq 19.0°$) and bright terrains ($0.9° \leq \bar{\theta} \leq 19.8°$) were found to be quite variable. For bright terrains, a uniform trend of increasing regolith porosity (decreasing h) with increasing roughness exists. While dark terrain Groups 4, 5, and 6 overlap this trend, Groups 1, 2, and 3 deviate from it significantly, but not in a systematic way.

In conclusion, this investigation has shown that the surface physical properties of Ganymede's principal terrains are considerably more variable than previously expected. The physical properties of some examples of dark terrain are similar to those of some examples of bright terrain. This suggests that the distinction between dark and bright terrain is not simple and that a continuum of terrains transitional between what have been called dark and bright terrains is likely to be present on the surface of Ganymede. The full geological significance of the terrain groups in Table 1 can only be appreciated if maps of the spatial distributions of these groups over selected areas and specific geological features are constructed (2,9). The correllation of photogeological analysis, structural/tectonic maps, and photometrically derived surface physical property maps should permit the specific characteristics of intermediate terrains to be identified in an interpretable geological setting (9,10). In the longer term, the ability to accurately portray the spatial variations in terrain surface physical properties can be greatly extended if Galileo images of particular regions of Ganymede (and other Galilean satellites) complement Voyager data in such a way as to provide images of identical areas over wide ranges of illumination and viewing geometries.

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Table 1

	REGION	w	h	b	c	$\bar{\theta}$	$\sqrt{\chi^2}$
Dark Terrain	Group 1	0.557±0.001	0.47±0.01	0.68±0.01	0.18±0.01	19.0°±0.5°	0.012
	Group 2	0.579±0.001	0.47±0.01	0.65±0.01	-0.00±0.01	8.8°±0.2°	0.009
	Group 3	0.423±0.006	1.04±0.16	0.75±0.03	0.25±0.04	14.8°±1.9°	0.010
	Group 4	0.579±0.001	0.46±0.68	0.67±0.01	0.07±0.01	0.3°±0.1°	0.017
	Group 5	0.517±0.001	0.93±0.01	1.05±0.01	0.10±0.01	1.0°±0.2°	0.017
	Group 6	0.720±0.006	0.15±0.02	0.97±0.04	0.74±0.05	13.2°±0.6°	0.013
Bright Terrain	Group 1	0.624±0.001	0.10±0.01	1.27±0.01	0.27±0.01	12.3°±0.1°	0.013
	Group 2	0.596±0.001	0.11±0.01	1.06±0.01	0.59±0.01	19.8°±0.5°	0.014
	Group 3	0.582±0.005	0.37±0.03	0.88±0.03	0.66±0.04	2.7°±3.4°	0.018
	Group 4	0.672±0.001	0.65±0.01	1.15±0.01	0.15±0.01	2.0°±0.1°	0.020
	Group 5	0.706±0.001	0.49±0.01	0.97±0.01	-0.03±0.01	0.9°±0.1°	0.013
	Group 6	0.714±0.013	0.76±0.29	1.08±0.07	0.18±0.08	1.5°±9.5°	0.006
	Group 7	0.901±0.001	0.49±0.01	0.15±0.01	1.05±0.01	4.8°±0.5°	0.004
	Group 8	0.762±0.001	0.63±0.01	0.58±0.01	1.27±0.01	1.6°±0.2°	0.011