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A NOTE ON HAPKE'S "BIDIRECTIONAL REFLECTANCE SPECTROSCOPY. 3. CORRECTION FOR MACROSCOPIC ROUGHNESS"

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ABSTRACT

B. Hapke (1984, Icarus 59, 41-59) has criticized the multiple-scattering theory of K. Lumme and E. Bowell (1981, Astron. J. 86, 1694-1704) by stating, in particular, that energy is not conserved. It is shown that Hapke's treatment is, in this respect, inferior to that of Lumme and Bowell, and itself violates the principal concepts of radiative transfer theory. Hapke's additional claim that, in Lumme and Bowell's work, the reflectance tends to zero at the limb is also refuted. Comment is made on the deduction of surface physical properties by modelling photometric observations.

1. INTRODUCTION

There has been considerable work on modelling the scattering of visible light in planetary regoliths. The most prominent feature in the phase curve of an atmosphereless body is the non-linear surge in brightness as the solar phase angle tends to zero. The first quantitative explanation of this effect was published almost a century ago by Seeliger (1887), whose "mutual shadowing" mechanism is still held to be valid. However, when applied to photometric observations of atmosphereless bodies, it has been realized that mutual shadowing alone is insufficient to explain the entire observed backscattered flux. To better match the observational data on the Moon, Hapke (1966) introduced the concept of surface roughness. Later, Lumme and Bowell (1981a, 1981b; hereafter LB) devised a radiative transfer model in which the effects of both mutual shadowing and surface roughness were taken into account. In addition, their model allowed for multiple scattering between regolith particles, which is particularly important for high-albedo surfaces. The way in which all three of these phenomena combine has been a matter of dispute for some time. Hapke (1982, 1984) has strongly criticized LB, asserting that the singly and multiply scattered components of the radiation field in a regolith must be affected by surface roughness in the same way or else energy will not be conserved. In a reply to Hapke's (1982) contention, Lumme and Bowell (1982) pointed out that the contrary situation obtains: namely, that the emergent flux would be <u>underestimated</u> if Hapke were correct. We show below, in a quantitative way, that such is indeed the case.

We also comment on a second criticism by Hapke (1984) of LB's modelling of the effects of surface roughness: that, contrary to observation, the reflectance tends to zero at the limb. Yet other disagreements that Hapke has with us, which were stated in his 1982 abstract but not elaborated on in his 1984 paper, we assume were answered by our short published reply (Lumme and Bowell, 1982) and by subsequent private discussions; we do, however, discuss the question of deducing the physical nature of a surface from light-scattering models.

2. CONSERVATION OF ENERGY

The calculation of radiation transport in a coherent scattering medium is a problem of the greatest difficulty unless simplifying assumptions are made. In the classical sense, radiative transfer involves light scattering in an infinite, horizontally homogeneous, plane-parallel medium in which the individual scatterers are in the far field (e.g., Chandrasekhar, 1960). However, when planetary regoliths are considered, two problems arise: first, the scattering medium is no longer horizontally homogeneous because of surface roughness; second, the individual scatterers (that is, particles) are not in the far field but rather touch each other. Horizontal inhomogeneity may be dealt with statistically, since, although locally disturbed, the observed surface has much greater dimensions than the roughness and is smooth on a large scale. Problems associated with the contiguity of particles are probably not serious since individual particles are thought, on average, to be much larger ($\gtrsim$10 μm) than the wavelength of light.

At the limit of geometric optics, the radiation field I can be divided into two components: one consisting of light scattered only once, termed the singly scattered component I_1; the other comprising light scattered twice or more, termed the multiply scattered component I_M. While I_1 is certainly affected by horizontal inhomogeneity (roughness) everywhere in the observed area, the effect on I_M is not at all clear *a priori*. It is here that there is sharp disagreement between the treatments of Hapke (1984) and LB. Hapke claims that both I_1 and I_M are affected equally since multiple scattering can occur only within a small surface element and not on the larger scale, as for example between surface elements. In contrast, it is assumed by LB that only I_1 is affected by roughness and that I_M is calculable using classical radiative transfer theory. It is qualitatively evident that Hapke's treatment *underestimates* the total emergent flux because a component of I_M is ignored. Thus, Hapke incompletely applies the concept of multiply scattered light which, by definition, comprises *all* light scattered more than once, regardless of the mechanism. In other words, Hapke considers that I_M "remembers" the direction of incidence (as does I_1), while we believe that I_M is subject to random-walk behavior. Naturally, LB's assumption that I_M may be treated by classical means is itself an approximation, although it is likely that deviations from the (unknown) correct directions of emergence of multiply scattered rays are random rather than systematic.

To verify quantitatively our statements regarding energy conservation in the Hapke and LB models, we have computed the Bond albedo A as a function of the rms surface slope $\overline{\theta}$ (in Hapke's notation) for conservative scattering; that is, when the single-scattering albedo $\tilde{\omega}_0 = 1.0$. Obviously, A = 1 = pq, where p is the geometric albedo and q is the phase integral, which is related to the phase function Φ by the well-known relationship

$$q = 2\int_0^{\pi} \Phi(\alpha)\sin \alpha \, d\alpha,$$

where α is the phase angle. For convenience, we further assume that the single-particle phase function is isotropic, that is, independent of the phase angle, although that assumption is not required. All the necessary equations are given by LB and Hapke (1984). From LB, we use Eqs. (25), (46), (47), and (49) in Paper I, and Eqs. (23)-(26) in Paper II, setting $x = 0$, $D = 0.37$, $\rho = 1.17$, $\tilde{\omega}_0 = 1.0$, and $g = 0$. Here, x is the contribution to the surface density by particles too small to cast shadows; D and ρ are, respectively, the volume density and surface roughness, with chosen values equal to averages derived from a large variety of atmosphereless bodies; and g is the asymmetry factor, the zero value being a consequence of the assumed equality of forward- and backward scattering for single particles [this assumption appears to be borne out by the results of modelling photometric data on the zodiacal cloud (Lumme and Bowell, 1985)]. From Hapke (1984), we use Eqs. (53) to (55)* and (65) to (67).

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*We note that Eq. (54) may be compared to its original form, Eq. (8) of Hapke (1963). The symbol g denotes the compaction parameter in the earlier paper and phase angle in the later one. We also note a misprint in the last term of Eq. (54).

The result of this comparison is given in Table I. Bond albedos A and geometric albedos p have been computed as a function of the rms surface slope $\bar{\theta}$ (= $\tan^{-1} \rho$) by means of a six-point Gaussian integration scheme. It can be seen from Table I that in both cases there are deviations from the nominal value A = 1.0, but that the deviations resulting from Hapke's model are much larger.

3. SURFACE BRIGHTNESS AND THE ROUGHNESS CORRECTION

As the second example of a "serious error" by LB, Hapke (1984) claims that the roughness correction "makes the reflectance approach zero at the limb." The general expression for the surface brightness I in our work is given by Eq. (39) of Paper I*. In refutation of Hapke's claim, we note that, at the limb, where the geometric quantity ξ (defined by Eq. (10) Paper I) tends to infinity, the surface brightness tends to 1-q, q being the fraction of the surface occupied by holes. Thus, unless the surface is entirely saturated with holes--presumably a physically unrealistic situation--the intensity at the limb is finite. The reduction by a factor 1-q affects the well-known Lommel-Seeliger spike in the brightness near the limb and

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*There is an obvious misprint in Eq. (39): the left member should be I_1 rather than I_0.

at least for the Moon, is not observed. Parenthetically, we note that Eq. (40) of Paper I, an approximation of Eq. (39), is to be used only for studies of the integrated brightness and not for the calculation of surface brightness.

4. DERIVATION OF PHYSICAL PARAMETERS FROM PHOTOMETRY

Hapke (1984) has also asserted that "while it may be possible to fit some astronomical data to [Lumme and Bowell's] theory, the relations between the deduced photometric parameters and actual surface properties of the body are unclear and are likely to be seriously in error." Since Hapke was unspecific in his criticism, it is difficult to know quite what he has in mind. However, we believe, along with Hapke, that modelled <u>optical</u> properties may not necessarily represent the <u>physical</u> nature of regoliths. It is obvious, for example, that the modelled volume density may overestimate the true volume density because of voids inside particles that play little or no part in the scattering of light; that the whole-disk optical properties may give no clue as to the heterogeneous nature of a surface on a small scale; and that, if particles in a surface have some preferential alignment, the physical nature of the surface could be erroneously deduced even though the photometric data were adequately modelled. However, we do believe that, in general, differences in the modelled optical properties are indicative of differences in the physical natures of the surfaces involved. In this regard, we think our inferences concerning Callisto (LB, Paper II) are useful, as is one of our basic conclusions in LB, Paper II that, except for albedo, the global optical properties of most atmosphereless bodies differ by only modest amounts.

We also believe that the average numerical values for the roughness ($\overline{\rho}$ = 1.17) and volume density ($\overline{D}$ = 0.37) obtained by LB are physically plausible; whereas values of the counterparts of these parameters derived by Hapke are not. The surface roughness has been discussed above in section II. For the volume density in regoliths, Hapke derives values of his parameter h that imply $0.03 \lesssim D \lesssim 0.1$. Direct, in situ measurements are, of course, lacking, though laboratory measurements on lunar fines indicate $D \approx 0.4$ (from Birkebak et al., 1971; and Greene et al., 1971), and for two particulate terrestrial samples D = 0.28 and 0.42 (Lumme et al., 1980). We find it hard to understand how planetary regoliths can be almost as porous as Saturn's rings, for which the modelled $D \approx 0.02$ (Lumme et al., 1983).

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TABLE I.

Comparison between Lumme and Bowell's (1981a) and Hapke's (1984) model for the case of conservative ($\omega_0 = 1$) and isotropic ($g = 0$) scattering.

	Lumme and Bowell		Hapke	
$\overline{\theta}$	A	p	A	p
20°	0.97	0.81	0.88	0.66
30	0.94	0.81	0.78	0.61
40	0.93	0.81	0.67	0.57
50	0.92	0.81	0.56	0.52
60	0.90	0.81	0.45	0.48