AN EXPERIMENTAL PHOTOMETRIC STUDY OF NATURAL GRANULAR SURFACE SAMPLES USING HAPKE'S MODEL.

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Introduction: Knowledge of the physical properties of planetary surfaces such as particle size and shape, roughness or compaction state, drawn from the interpretation of photometric data, has been improved over the last past decades with the parallel development of numerical and semi-empirical models and remote sensing techniques. Widely used for the photometric study of regoliths is Hapke's semi-empirical bidirectional reflectance model [1], which uses six parameters to characterize a material from reflectance data acquired with various angular and illumination conditions. Such observations are difficult to achieve from Earth-based telescopes, and orbital data still appear to lack enough observational diversity (e.g., [2, 3, 4]). In this context, photometric laboratory measurements on controlled materials with multiangular ranges as wide as possible are mandatory to provide ground truth and benchmarks to help interpret remotely sensed data depending on the available geometry conditions. So far, few photometric experiments, mainly on synthetic materials, have been undertaken ([3, 5, 6, 7, 8, 9, 10]). Natural surface samples have been poorly explored, motivating the present work. In order to study a wide range of physical characteristics that influence the photometric behavior of a material, volcanic samples have been chosen with diverse contents of rock fragments, mineral fragments and glass, various shapes and surface aspects, and sizes varying from the micron-scale to the millimeter-scale.

Multiangular data of these samples measured with the spectro-imaging facility setup ISEP at the Midi-Pyrénées Observatory (OMP, Toulouse, France [5]) have been inverted using Hapke's 1993 model along with a dedicated genetic algorithm to reproduce bidirectional reflectance variations with viewing geometry.

Samples description and data acquisition: Volcanic materials from different origins have been used, including samples made of mineral and glass particles: fresh basalt (France), volcanic sand (Iceland), pyroclastics (Japan), olivine (Hawaii), basalt (Hawaii), amorphous basaltic glass (controlled melt of fresh basalt). Some samples are homogeneous (e.g., olivine) while others are heterogeneous, consisting of complex mixtures (e.g., pyroclastics); accordingly, the role of the sample composition and texture on the photometric modeling can be addressed. The different materials were either sorted into their original grain sizes or ground into predefined granulometric classes, all between a few tens of μm to 2 mm. Inversion models being based on geometric optics, particles with a size on the order of the wavelength of the light or smaller are inappropriate; on the other hand, when working with visible light, particles larger than the millimeter scale behave similarly, being thousands of time larger than the wavelength. As experimental studies in spectroscopy are generally constrained by powders made of particles with sizes ranging from <30 μm to 250 μm only (RELAB, [11]), the present work endeavors to widen this size distribution to better comprehend the optical role of larger grains.

The spectral imaging facility ISEP measures the bidirectional reflectance of macroscopic targets (6×4 cm², maximum 10 mm thick), using a spectralon as a reference during measurements, and acquires images in the visible and near infrared domain (559 nm, 699 nm, 791 nm, 880 nm and 960 nm). About 20 geometrical configurations have been carefully chosen in order to: (1) span the multiangular space as regularly as possible in terms of incidence, emission and phase angles (phase between 25° and 130°); (2) contain more than half of the measurements out of the principal plane (i.e. with varying azimuths), as tests showed that the use of measurements out of the principal plane adds significant constraints on the parameters; (3) lead to parameter estimates close to those derived from hundreds of varied configurations. The last requirement has been verified by means of simulations using datasets with hundreds of configurations from Bloomsburg's BUG lab [10]. Due to technical limitations, no phase angle smaller than 25° can be measured, thus precluding the study of the opposition effects that take place near zero phase.

Inversion method: Hapke's 1993 model relies on six parameters, but due to the absence of small phase angles, only four are discussed here: the macroscopic roughness θ ($0° \leq \theta \leq 45°$), the single scattering albedo w ($0 \leq w \leq 1$), the asymmetry parameter b ($0 \leq b \leq 1$) and the backscattering fraction c ($0 \leq c \leq 1$). The last two are included within the phase function described by a 2-terms Henyey-Greenstein function (e.g., [8, 12, 13]). ISEP data have been inverted using a dedicated genetic algorithm that has been developed and successfully implemented earlier [2, 5, 6, 14, 15]. With this method, the whole set of Hapke's parameters is treated simultaneously without any a priori assumption, so that the risk of meeting a local minimum is limited in comparison to other techniques of inversion, and it is far less time-consuming than random searches such as in the Monte Carlo method.

Results and analysis: Using the retrieved photometric parameters from the genetic algorithm, modeled phase functions have been computed and compared with the observations, giving very satisfactory matches for the great majority of samples, in accordance with their small residuals. Very few cases showed less satisfactory fits between observations and model, which could be explained either by data acquisition problems or, more likely, a difficulty inherent to Hapke's model to deliver unambiguous solutions when dealing with materials made of complex mixtures. Regarding the well-modeled samples, general trends can be seen.

As was expected from the differences in the absolute reflectance between the small and the large particles of a same material [9], the single scattering albedo w increases when particles get smaller.

Materials with broad scattering lobes (i.e. $b \leq 0.5$), have relatively large modeled surface roughness (θ about 15-25°), the value of θ seemingly increasing with grain size for these samples. They also tend to become more backscattering as grain size increases, an observation in agreement with previous findings that the forward scattering of smaller particles tends to be stronger compared to larger particles for a given material [3]. But for some samples that do not display the same shape and/or composition with respect to grain size (e.g., volcanic sand, fresh basalt), the observed evolution of the photometric parameters could be ascribed to both a slight difference of the powders' composition and a size change.

Materials with narrow scattering lobe (i.e. $b \geq 0.5$) are all extremely forward-scattering ($c < 0.1$) and their scattering lobes tend to become narrower (increase of b) as grain size increases. As the concerned grains display similar aspect regardless of their sizes, this last observation seems indeed uniquely induced by the change of particle size, though one cannot rule out possible minor variations in the sample's structure with respect to grain size. Their modeled surface roughness are relatively small (<15°) and the narrower their scattering lobes, the smaller their θ. All these materials have in common a proportion on the order of 30% or more of fresh glass or isolated monocrystals, which suggests that from this proportion and above, glass and monocrystals dominate the photometric response of a material.

Following [8] who worked on artificial isolated particles, this work's results for natural surface samples have been displayed on a c vs. b plot. They appear scattered on a similar L-shaped trend as in [8], but samples comprising a large proportion of fresh glass or monocrystals clearly extend and explore some new part of the trend, being extremely forward-scattering with narrow scattering lobes. As regards particles that do not contain either a high proportion of fresh glass or isolated monocrystals, round particles tend to be more backscattering than blocky or irregularly-shaped ones, with an overlap around $c=0.5$. Samples with a significant amount of hollowed particles tend to be more backscattering than those made of solid particles only. This is in agreement with the fact that the presence of voids within particles is among several characteristics noticed to have a strong backscattering efficiency [16].

Conclusion: This study was primarily designed to establish benchmarks for orbital multiangular data analysis, and of interest for this purpose is the experimental finding that a set of a few tens (20-30) of well-chosen multiangular measurements can be sufficient to allow photometric studies of a surface, provided that large values (~ 130° or more) of phase angles are present and acquisitions are made with varying azimuths. Specific photometric characteristics of natural materials have been found from the study of various natural volcanic samples. The results should help to better interpret present and to come orbital photometric data from airless bodies' surfaces such as the Moon's or Mercury's regoliths.

References: [1] Hapke B. W. (1981) *JGR, 86,* 3039–3054; Hapke B. W. (1986) *Icarus, 67,* 264–280; Hapke B. W. (1993) *Cambridge Univ. Press, New York*; Hapke B. W. (2002) *Icarus, 157,* 523–534. [2] Jehl A. et al. (2008) *Icarus, 197,* 403–428. [3] Kamei A. and Nakamura A. M. (2002) *Icarus, 156,* 551–561. [4] Kaydash V. et al. (2009) *Icarus, 202,* 393–413. [5] Cord A. M. et al. (2003) *Icarus, 165*, 414–427. [6] Cord A. M. et al. (2005) *Icarus, 175*, 78–91. [7] Hapke B. W. et al. (2009) *Icarus, 199*, 210–218. [8] McGuire A. F. and Hapke B. W. (1995) *Icarus, 113,* 134–155. [9] Okada Y. et al. (2006) *J. Quant. Spectrosc. Radiat. Trans., 100,* 295–304. [10] Shepard M. K. and Helfenstein P. (2007) *JGR, 112,* E03001. [11] Pieters C. M. (1983) *JGR, 88,* 9534–9544. [12] Hartman B. and Domingue D. L. (1998) *Icarus, 131*, 421–448. [13] Johnson J. R. et al (2006) *JGR, 111,* E02S14. [14] Pinet P. C. et al. (2004) *LPS XXXV,* Abstract #1660. [15] Chevrel S. D. et al. (2006) *LPS XXXVII,* Abstract #1773. [16] Warell J. et al. (2010) *Icarus, 209*, 138–163.