SIZE-DEPENDENT MEASUREMENTS OF THE SCATTERING PROPERTIES OF PLANETARY REGOLITH ANALOGS: A CHALLENGE TO THEORY.

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Introduction: The nature of the scattering of light is thought to be well understood when the medium is made up of independent scatterers that are much larger than the wavelength of that light. This is not the case when the size of the scattering objects is similar to or smaller than the wavelength or the scatterers are not independent. In an attempt to examine the applicability of independent particle scattering models, to planetary regoliths, a dataset of experimental results were compared with theoretical predictions.

Method: Light scattering by samples of three well-characterized powders (aluminum oxide, calcium carbonate, and iron oxide) were analyzed. Particle sizes of the samples range from smaller than to larger than the wavelength. Scanning electron microscope (SEM) analyses were performed to try and determine the actual particle size distribution of the sample. However, due to the difficulty of obtaining precise results with small particles, the SEM results are questionable, and the manufacturer's labeled sizes are assumed to be accurate. The samples were analyzed using both the long arm ($0.05° <$ phase angle (g) $< 2.5°$) and short arm ($5° < g < 140°$) goniometers in the Goniometer Laboratory at JPL. Instrument descriptions and data for a variety of samples have been previously reported [1-5].

A comparison with predictions of scattering models was made by first calculating scattering parameters from the goniometer data. These were determined by fitting the radiative transfer-based, improved model of [6] to the curves. The parameters fitted are the single scattering albedo (w), single particle scattering function (p(g)) and the coherent backscatter angular width parameter h_c. The single particle scattering function was represented either as an expansion of Legendre polynomials (2nd or 3rd order), or as a double Henyey-Greenstein function (symmetric or asymmetric), depending on which representation produced the best fit to the data. Where the opposition effect was wide enough to affect the short arm goniometer data, both the shadow-hiding and coherent backscatter opposition surges were then fit to this dataset. When this was not possible, the data from the long arm goniometer were fit using a simplified set of equations that contain only terms for the coherent backscatter opposition surge and the background intensity. The resulting fit parameters were then combined [6] to calculate fundamental scattering variables: transport mean free path (L), average scattering angle $\langle\cos\theta\rangle$, scattering coefficient (S), and extinction coefficient (E).

A Mie code [7] was used to calculate scattering parameters of regoliths of independently scattering spherical particles of the same sizes and refractive indices. Values of the complex refractive index for the iron oxide were obtained from [8]. Values of the imaginary portion (k) for the remaining samples were estimated using an equivalent slab model [9] and published values of the real part (n) of the refractive index [10]. Due to the extreme width of the coherent backscatter opposition surge observed in the iron oxides, the relationship between h_c and L [6] is of doubtful validity [11], so calculation of scattering parameters for these samples is not possible using the methods outlined above, although comments made about w, $\langle\cos\theta\rangle$ and h_c still apply.

Results: The measured parameters show very little dependence on particle size. The single scattering albedos of the iron oxides are the only exception to this, where a decrease in albedo is observed with increasing particle size. This is expected because of increasing absorption with increasing size.

The average scattering angle $\langle\cos\theta\rangle$ is negative for nearly all samples, showing that the samples are backscattering. This is contrary to theory, which predicts that high albedo particles are highly forward scattering.

The measured and predicted values of the transport mean free path (L) for the aluminum oxide samples are plotted in Figure 1. The results show that while the independent scattering Mie model predicts a large change in L as the particle size approaches the size of the wavelength, such a change was not observed in the laboratory. In fact, the samples used here all show similar values of L regardless of particle size.

The measured extinction and scattering coefficients (E and S) also do not agree with trends predicted by theory. The value of S stays relatively constant throughout the particle size suite, while E varies due to the decrease in w with increasing particle size. This is contrary to theory, which predicts that S increases with decreasing size down to the wavelength and then decreases thereafter. Values of S for both measured fits and model calculations for the aluminum oxides are shown in Figure 2.

The coherent backscatter peaks for all the materials measured were sharply cusped. However, theory [11] predicts that the peaks should be rounded for materials with albedos less than one. This cusping implies a non-negligible number of long photon scattering paths even when the particles are absorbing.

Conclusions: Laboratory measurements of scattering by particulate media disagree strongly with predictions of models that assume the particles scatter independently. This assumption is a crucial one made by all present models of light scattering by media of closely spaced particles. Our results indicate that there are important gaps in our understanding of the scattering of electromagnetic radiation by planetary regoliths.

References:
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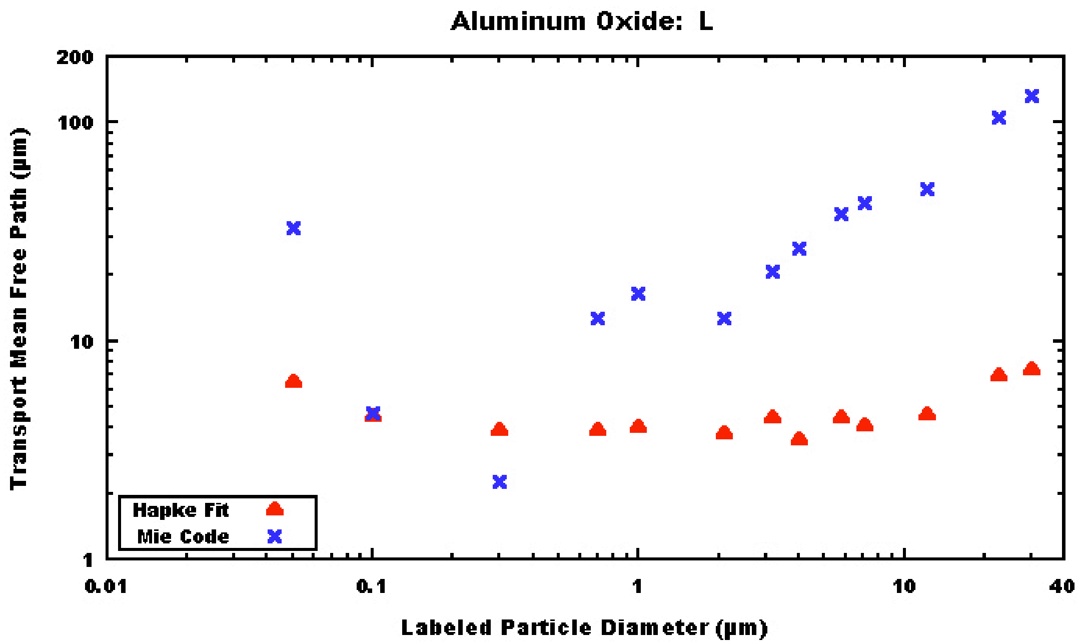

Figure 1: Values of L for measured (red triangles) fits and model (blue crosses) calculations for aluminum oxide samples.

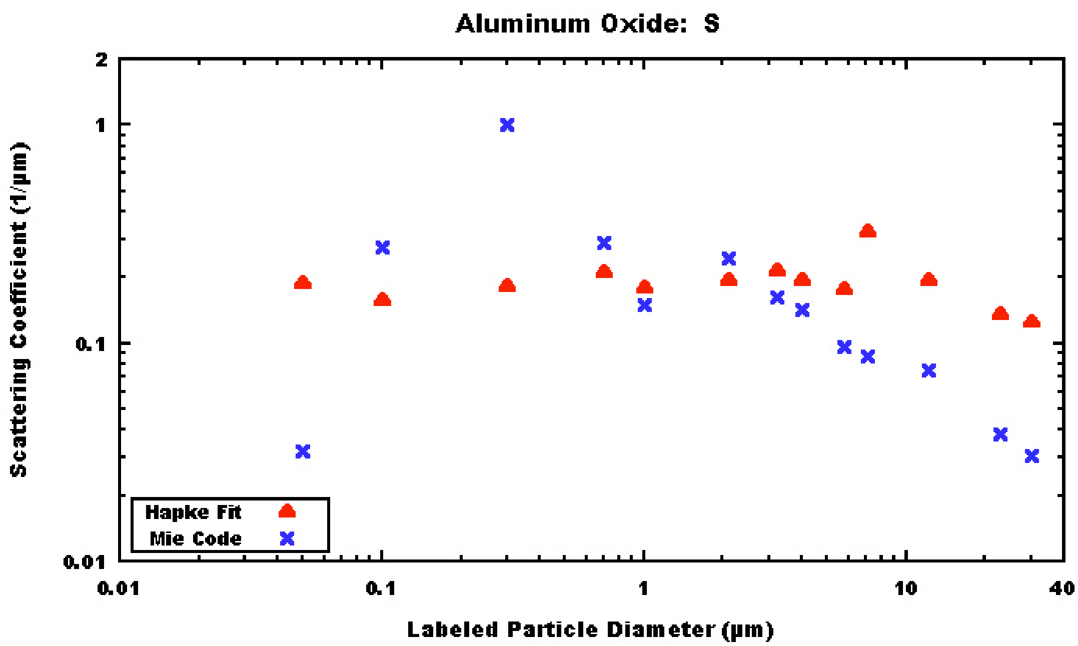

Figure 2: Values of S for measured (red triangles) fits and model (blue crosses) calculations for aluminum oxide samples.