LABORATORY SIMULATIONS OF PLANETARY SURFACES: INTERPRETING REMOTE SENSING DATA IN TERRESTRIAL CONTEXT.

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Introduction: We present laboratory measurements of the photometric properties of particulate materials of high reflectance. These materials simulate planetary regoliths of the type expected on high albedo atmosphereless solar system bodies (ASSBs). These measurements of the reflectance and polarization phase curves were taken with a goniometric photopolarimeter (GPP) of new and unique deisgn. Our GPP employs the Helmholtz Reciprocity Principle (HRP); i.e., the incident light is linearly polarized and the intensity of the reflected component is measured [1,2]. Instruments of this type are generally classified as a "polarization-sensitive well-collimated radiometers" and the particulate samples are classified as "discrete random media" [3]. We have shown that HRP lab measurements are physically equivalent to remote sensing angular scattering measurements of reflectance and polarization of atmosphereless planets and small bodies [4].

We note that this work suggests an interesting terrestrial application perhaps relevant to geo-engineering efforts to mitigate Earth's changing climate, particularly to the application of atmospheric aerosols to accomplish solar radiation management (SRM). We stress that in the best of possible circumstances this hypothetical SRM concept would only be a palliative approach while society addresses the imperative of reducing the anthopogenic concentration of greenhouse gasses in the atmosphere.

The Measurements: We used a GPP to measure the reflectance and polarization phase curves of 13 well-sorted particle size fractions of aluminum oxide (Al_2O_3), an industrial optical abrasive, with diameters $0.1 \leq d \leq 30$ µm. These samples are identical to those studied in our previous experiments where we measured phase curves of the reflectance $R(\alpha)$ and polarization degree $P(\alpha)$ and addressed the amount of multiple scattering in the materials by measuring the phase angle dependence of the circular polarization ratio [5,6,7]. We developed two empirical expressions that are excellent approximations to $R(\alpha)$ and $P(\alpha)$ of a bright particulate material for $\alpha < 15^o$. The reflectance phase behavior is approximately described by PSIMTSAC1 $y= \cos(\alpha/2)\,(a \cdot \exp(b \cdot \alpha) + c \cdot \exp(d \cdot \alpha)$ The polarization phase behavior can be described by (PSIMTSAC 2):

$P = -\alpha / (1 + a_p \exp(b_p \alpha^{c_p}))$, where a_R, b_R, c_R, where a_R, b_R, c_R, d_R, a_p, b_p, c_p are least square fitting constants. A typical reflectance phase curve is shown in Fig. 1.

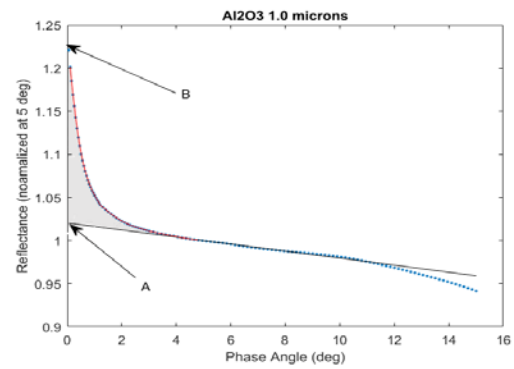

Fig 1. Phase curve for 1.0 µm Al_2O_3 particles. A straight line is fitted to the data from 5-10°. This is extrapolated to 0°. The size of the opposition surge is estimated by two methods. First, we calculated the area (shaded) area between the linear region and the phase curve normalized at 5°. Second, we calculated the difference between the extrapolated linear portion of the curve at 0° (A) and the size of the phase curve at 0°(B).

Following the methodology discussed above we are able to estimate the size of the opposition surge by: (1) calcuating the size of the peak when $\alpha=0°$ and (2) calculating the area under the phase curve (the shaded area shown in Fig 1. For all of our Al_2O_3 particulate samples we find that the backscattering is maximum when $\pi D/\lambda = \sim 1$, where D is the particle size and λ is the wavelength of the incident radiation. This is in qualitative agreement with theoretical predictions [8]. The backscattering effectiveness of any particulate depends on the area under the phase curve.

The Terrestrial Application: The Al_2O_3 materials that we pioneered for GPP measurements are highly reflective. We independently noted over the years the widespread discussion in the scientific community regarding the emplacement of various aerosols in the atmosphere for the purpose of SRM. In 2007 we calculated that the amount of Al_2O_3 of appropriate particle size to offset the anthropogenic solar forcing function is surprising small. We did not publish the results because of the hazardous nature of such a geo-engineering proposal. (Al_2O_3 has a Mohs hardness of nine, and the prospect of subjecting the population of air-breathing animals to the ravages of silicosis-related diseases is undesirable). We continued a quest for other, more benign materials that might accomplish the same effect.

We were unaware that Al_2O_3 aerosols had previously been suggested, and were surprised when one of our students recently discovered a 1997 proposal by researchers at the Lawrence Livermore Laboratories that advocated the widespread distribution of Al_2O_3 as an aerosol for SRM [9]. (Obviously the LLL team did not share our concern regarding the distribution of high-hardness aerosols and widespread lung disease).

In late 2015 we investigated of the optical properties of highly reflective evaporite salts for possible application to understanding evaporite deposits on other solar system bodies, particularly Ceres (see companion paper by Li et al. at this meeting). We studied the reflectance and polarization properties of Na_2CO_3 and the of lower molecular weight alkali halides, specifically NaCl and KCl. We found NaCl has reflectance properties remarkably superior to Al_2O_3, for the purpose of SRM. It is obviously a candidate deserving of further exploration for SRM application because of its benign effect on air-breathing organisms.

Figure 2 shows the relative reflectance phase curves of three evaporite materials. Al_2O_3 is shown as red dots, Na_2CO_3 as green triangles, and NaCl as blue crosses. All three particulates are of approximately 30 μm particle size. The data are normalized at 10°, where all three materials have a reflectance comparable to Spectralon®. Based on our previous work we anticipate that the phase curve for NaCl will broaden still further as paricle size decreases until $\pi D/\lambda$ =~1. We suggest that **if** NaCl particles are of appropriate morphology **and** of small particle size **and** in the form of dispersed discrete random media, **then** they will be highly reflective at **u**ltraviolet, **b**lue and **v**isual (UBV) wavelengths and transparent in the infrared. We suggest that even relatively small quantities of materials (with reflective properties of NaCl) distributed as atmospheric aerosols might reduce insolation at Earth's surface by several W/m^2, the amount estimated by the IPCC to be the anthropogenic contribution to greenhouse warming.

Future Work: We suggest investigating the reflectance and polarization of NaCl in particulate form at sizes larger than, approximately equal to, and smaller than $\lambda_{0.5\mu m}$ to understand these questions further.

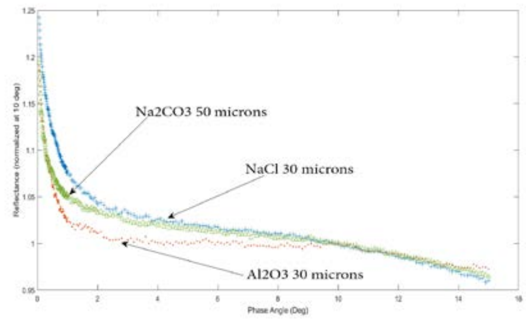

Fig 2. Reflectance phase curves of Al_2O_3 (red dots), Na_2CO_3 (green triangles), and NaCl (blue crosses). The data are normalized at 10° where all three materials have comparable reflectance relative to the reflectance of a Spectralon® reflectance standard. The far broader phase curve of NaCl is a consequence of the cubic crystal structure of NaCl compared to the platelet crystal structure of Al_2O_3.

Afterthought: We note the serious ethical concerns associated with geo-engineering concepts. These have been widely discussed in two reports of the National Academy of Sciences (2015) and in the popular literature [10]. We have expressed these ethical concerns clearly in our publications stating that, with great trepidation, we suggest further investigation into the feasibility of initiating pilot programs to consider temporary regional application to mitigate short-term, life-threatening conditions in areas where extreme temperature events are forecast. We recognize that a localized approach may not fit the definition of geo-engineering due to its regional nature, but global application might be considered for immediate relief during a near-term 'transition period' while society acts to reduce anthropogenic greenhouse gas. This transition period might span several decades. *This is a palliative, not a solution, somewhat analogous to the application of morphine in a medical situation.*

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